N63 21913

CODE-1

105p.

OTS PRICE

XEROX $ 9.10 ph

MICROFILM $ 3.35 mf.

NASA CR 51278

GD

GENERAL DYNAMICS
ASTRONAUTICS

A2136-1 (REV. 6-61)

AY62-0031

15 August 1962

THE FINAL REPORT FOR THE GENERAL DYNAMICS/ ASTRONAUTICS ZERO-G PROGRAM COVERING THE PERIOD FROM MAY 1960 THROUGH MARCH 1962

Contract No. AF18(600)-1775

NASA-8-2664

N63-21913

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FOREWORD

This final report documents the results of the General Dynamics/Astronautics analytical and experimental zero-g program performed in support of the Centaur Design and Development Program. The program was initiated in May 1960 and completed in March 1962 under sales order number 12-1-54.

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SUMMARY

A theoretical and experimental zero-gravity (zero-g) program was carried on from May 1960 through March 1962 at General Dynamics/Astronautics in support of the Centaur Design and Development Program. This program was a continuation of preliminary zero-g studies performed at General Dynamics/Astronautics in 1959, and in early 1960 on a C131B aircraft. The preliminary tests were instrumental in defining potential zero-g problem areas and problems connected with obtaining quality results from experimental zero-g testing in an aircraft. The test results obtained from the second phase of the program, and presented in this report, provided design criteria and design evaluation of a number of Centaur items. Both qualitative and quantitative zero-g data was obtained in the areas of liquid behavior, venting, heat transfer and instrumentation. An indirect result of the test program was the development of zero-g testing methods which will produce quality results, and the knowledge gained in handling of cryogenic liquids in this special environment. It is felt that this latter consequence of the test program will be very useful in planning future zero-g test programs.

The experimental program consisted of laboratory, aircraft and ballistic missile tests. The result of an agreement with the Aeronautical Systems Division at Dayton, Ohio permitted use of both a C131B and KC135 aircraft as a test facility. An agreement with the NASA Lewis Laboratories provided for the use of Aerobee missiles for several tests with General Dynamics/ Astronautics hardware.

The most significant achievements of the zero-g program with specific application to Centaur are summarized as follows:

(1) The parameters governing the liquid-gas configuration in the Centaur tanks are now well known. The equilibrium shape of the ullage bubble is governed by the contact angle, surface tension effects, tank geometry and liquid-vapor volume ratios. Experimental results and a theoretical analysis has shown that the liquid hydrogen in general will wet the wall with the vapor bubble in the center. A partial understanding of the scaling principles was obtained which describes the effect of size and liquid properties on the transient or oscillatory behavior of the liquids in zero-g.

(2) The behavior of the General Dynamics/Electronics hot wire liquid-vapor sensor has been established. As a result data reduction from vehicles F-1, F-2, and F-3 should yield useful information.

(3) For a maximum expected heating rate on the Centaur cylindrical tank walls of a 25 Btu/hr-ft^2, boiling will most likely occur while the vehicle is in the parking orbit and transfer ellipse. The bubbles formed at the heated surface will coalesce and the surface tension forces will be sufficient to rewet the surface behind the bubble for an undetermined period of zero-g time.

(4) No additional complications to the settling problem (prior to an engine re-start) need be feared from the eventuality of liquid hydrogen impinging against warm unwetted surfaces. There will be no appreciable rejection of the liquid.

(5) Centaur orientation maneuvers will cause considerable liquid rotation, but will not cause the liquid to be dispersed throughout the tank. These test results make the feasibility of venting the Centaur tank with a center vent tube more attractive.

(6) The center vent has excellent potential as a venting device for Centaur. Analytical and experimental studies verified that only a small portion of a tube inserted into the ullage region of liquid and gaseous hydrogen in a zero-g environment would be wetted. Liquid disturbances caused by the venting process will not cause liquids to be vented for expected Centaur vent rates and liquid-volume ratios during the parking orbit and transfer ellipse.

(7) The results of outflow tests simulating Centaur propellant settling, chilldown and main engine start sequences showed that:

   (a) The first pre-start sequence can be performed without firing the settling rockets.

   (b) The second pre-start sequence can be accomplished by firing only two of the four settling rockets.

   (c) The third pre-start sequence can be accomplished by firing two rockets to settle the propellants and four rockets at the start of chilldown flow.

(8) The ullage control surface, designed for Centaur, will not serve the purpose for which it was intended. A quarter section of a right truncated cone was fabricated and placed in front of the

fuel tank boost pump outlet to contain a greater quantity of liquid in this region prior to main engine start, and thus eliminate the need for firing the settling rockets. Results of the outflow tests showed that the surface was ineffective because the inertial forces which produce gas flow are considerably greater than surface tension forces resisting gas pull-through.

As pointed out previously, the experience gained in zero-g testing techniques and in handling of a cryogenic liquid is particularly important for planning future zero-g test programs. Results of approximately 35 flights on the KC135 aircraft in the summer of 1960 clearly demonstrated the difficulties in developing a "free floating" technique for the test capsules. Useable zero-g times of from 9-15 seconds every 1 out of 3 manuevers was finally obtained. The KC135 was theoretically capable of 30 seconds. Furthermore, the test results in most instances were not repeatable because of the difficulties experienced in releasing the test capsule into a zero-g environment. Often considerable agitation of the test liquid was produced due to small deviations of the aircraft from the desired trajectory. These problems, combined with the elaborate safety kit system which had to be fabricated to meet Air Force safety requirements while testing with liquid hydrogen, delayed the test program, and in some instances, seriously limited the quality of test results which could be obtained. In contrast the drop tests, although limited to one or two seconds of zero-g time, yielded in most instances very useful results. The use of small models is a disadvantage in some instances, but as increased knowledge of the laws governing the transient behavior of liquids in a zero-g environment is gained, this disadvantage should be eliminated. It is felt that in most cases drop tests are preferrable to aircraft tests.

The test schedule had to be revised several times during the program due to problems not anticipated when the program was initiated in May 1960. The primary delay in the program occurred from September 1960 through February 1961, and was caused by difficulties experienced in fabricating and installing the safety kit system in the aircraft. In March 1961, the liquid hydrogen flights were initiated on the KC135 aircraft and were completed by the first of August. A total of 28 flights were performed during this period of which 18 were liquid hydrogen flights. The remaining 10 flights were system checkout and crew training flights with liquid nitrogen as the test fluid. In August 1961, General Dynamics/Astronautics was notified that the aircraft would be grounded until November due to mechanical difficulties, and the C131B was offered as a replacement for completion of the program. However, due to the construction of a two second drop facility and increased knowledge of the scaling laws, General Dynamics/Astronautics decided that the remainder of the tests could be accomplished in the laboratory drop facilities.

The knowledge gained as a result of this program did furnish much needed design criteria and hardware evaluation for Centaur. In some areas of investigation, sufficient quantitative data were obtained to recommend changes which would optimize vehicle performance and/or design. In other areas, the available test facilities limited the test results to short time zero-g effects. In the final analysis, the results presented here cannot be completely verified until the first Centaur flight.

INTRODUCTION

During the coast periods between firings, the Centaur vehicle will be in an approximate zero-g condition for periods of several hours. The vehicle tanks will be partially filled with liquid oxygen and liquid hydrogen. The design and reliability of the vehicle will be affected to a considerable degree by this zero-g phenomenon. When the Centaur program was initiated, a very limited amount of information was available for prediction of the liquid-gas configuration in the Centaur tanks at the beginning, during, and following periods of zero-g. The liquid condition affects heat transfer, and subsequently, boil-off rates, as well as the operating characteristics of the pumps following a zero-g flight. To optimize vehicle design, the designer must be able to accurately predict the statics and dynamics of liquid-gas interfaces under low and zero-g conditions. Therefore, in May of 1960 an experimental and theoretical zero-g program was initiated in support of the Centaur Design and Development Program. This program was an extension of a preliminary test program carried on in 1959 and early 1960 to investigate the problems of heat transfer and venting of cryogenic liquids during a zero-g condition. These early tests were performed on an Air Force C131B aircraft.

Prior to understanding the effects of zero-g on a Centaur vehicle, a definition of zero-g is necessary. In a generalized way, zero-g may be defined as the condition experienced in orbital motion by relatively low mass bodies such as artifical satellites. Zero-g is a balanced force condition producing weightlessness. The weightless state exists throughout the entire solid, liquid or gas. All other mass properties are unchanged.

No problems are encountered with solid objects in the zero-g state. Gases may present a heat transfer problem due to absence of conventional free convection in a zero-g environment. However, liquids present the major share of zero-g problems because of their distribution. Liquids in zero-g will occupy spaces previously occupied by gases because they are no longer confined to one end of a container due to gravitational forces.

The zero-g studies were primarily aimed at investigating problems associated with the Centaur liquid hydrogen tank. Because of the Centaur structural design, the hydrogen tank presented the major share of zero-g problems in the areas of investigation undertaken during this program. A sketch of the Centaur is shown in Figure 1 to familiarize the uninitiated reader with the Centaur vehicle.

Tests were performed in four basic areas. Liquid behavior studies were performed to determine the behavior of cryogenic liquids in the Centaur tanks at the beginning of, during, and following periods of zero-g. Heat transfer studies were conducted to obtain both quantitative and qualitative data of the heat transfer phenomena in a zero-g environment. An evaluation of two vent devices was performed to determine if venting of the vapor during the zero-g boil-off condition would occur without a coincidental loss of the liquid portion of the cryogenic propellant. Instrumentation tests were conducted to check the performance of currently available liquid-vapor sensors at zero-g and at liquid hydrogen temperatures. Whenever possible liquid hydrogen was used as the test fluid in order to simulate as closely as possible Centaur conditions. Analytical studies were also performed to provide where possible a theoretical basis for observed experimental results.

This final report presents in detail, with one exception, the results of the General Dynamics/Astronautics zero-g investigations performed in support of the Centaur Design and Development Program and covers the period from May 1960 through March 1962. The one exception is the Aerobee test results which have not been completely analyzed at this time, and therefore will be reported in a separate document at a later date. However, where applicable, the Aerobee test results known to date are mentioned in this report. The final report consists of the following three parts:

(1) Thirteen separate reports covering in detail all phases of the test program.

(2) A section containing a comprehensive review of the program with emphasis on the results and applications to Centaur.

(3) A composite motion picture film of the tests which were performed.

The section containing the comprehensive review of the program is an attempt to present to the reader, who may not have sufficient time or the need to review the program in detail, the major aspects of the General Dynamics/Astronautics zero-g investigations with emphasis on the results and applications to the Centaur vehicle. This section of the report also contains a Bibliography of all General Dynamics/Astronautics zero-g reports published as part of this program. The first 13 reports listed specifically form a part of this final document and are referenced throughout the section containing the comprehensive review of the program.

SKETCH OF CENTAUR VEHICLE

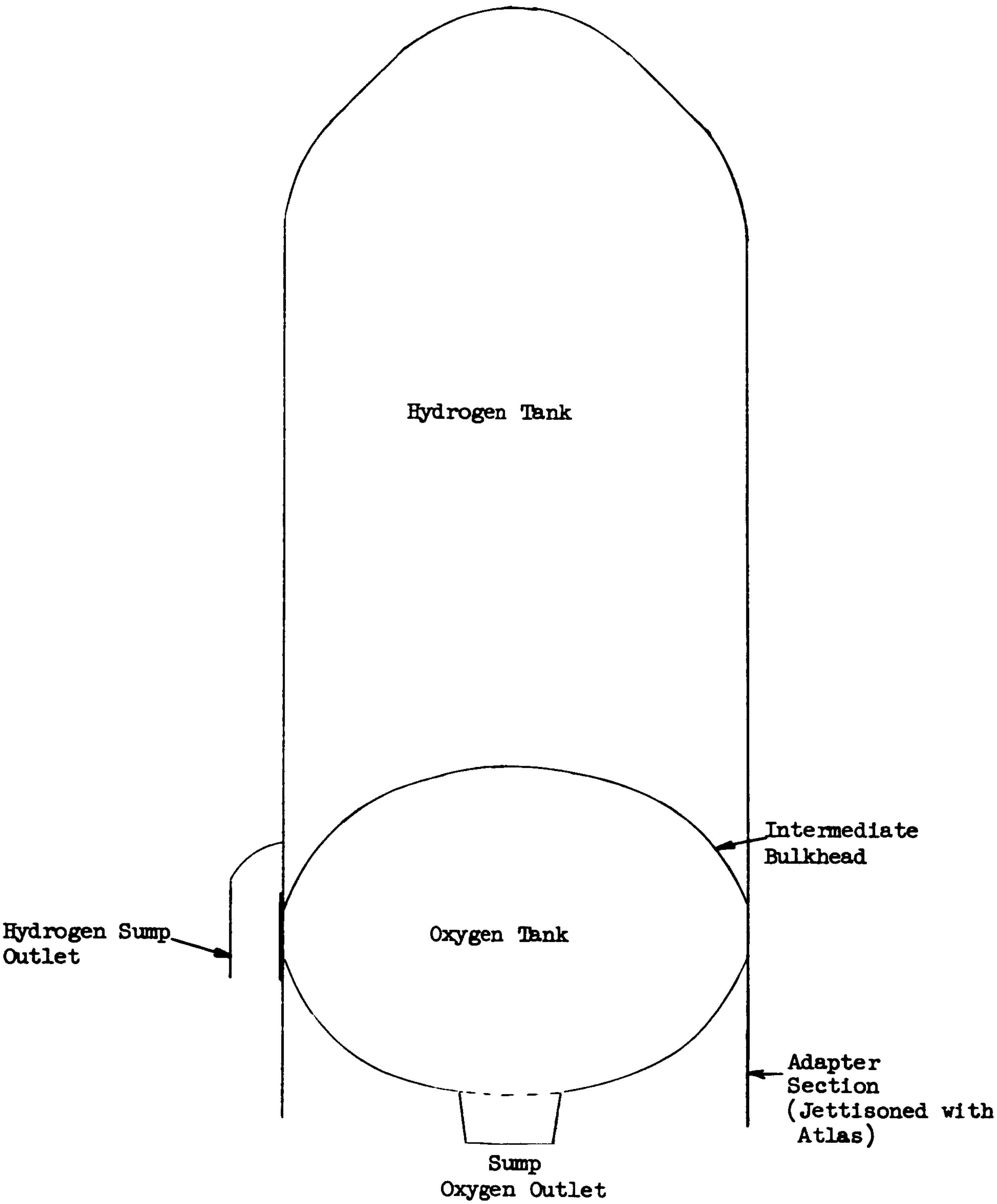


FIGURE 1

I. METHODS OF INVESTIGATION

Both analytical and experimental studies were performed to investigate the potential engineering design problems associated with the behavior of liquids in a zero or near zero-g environment. Emphasis was placed on the behavior of cryogenic liquids and those liquids which could be used to simulate the behavior of liquid hydrogen in model tests. The analytical approach was to develop mathematical equations which describe the equilibrium spatial configuration of the fluid in a zero-g environment and to investigate the effect of size and liquid properties on the transient and oscillatory behavior of the liquid in a low and zero-g condition. The analytical treatment provided a basis for the interpretation of the experimental model test results.

The experimental test methods included the linear drop test tower, aircraft tests and ballistic missile tests. Zero-g times of 1 second to 5 minutes were obtained with these test facilities.

A. Analytical Approach

The Astronautics analytical treatment of a liquid in a zero-g field is covered in detail in References 15 through 22. With particular application to Centaur, the spatial configuration of the liquid hydrogen in the Centaur fuel tank during a coast period may be approached by considering the principle of minimum surface energy, which states that the total of surface energy, for a stable configuration of the liquid, is a minimum. Assuming the absence of unbalanced forces, (mechanical or thermal), and denoting the contact angle between the liquid and solid by θ, the surface energy per unit area of vapor to solid (tank wall) by γ_{VS}, that of the liquid to solid by γ_{LS}, ana that of liquid to vapor by γ_{LV}, it is known that the following relation holds:

$$\gamma_{VS} = \gamma_{LS} + \gamma_{LV} \cos \theta$$

(This relation is valid for all liquids, wall wetting or non-wetting). For liquid hydrogen the contact angle is zero and therefore the following relation holds:

$$\gamma_{VS} > \gamma_{LS}$$

As a result of the principal of minimum surface energy, if there is sufficient liquid to wet the wall, γ_{VS} will be replaced by γ_{LS}, thereby minimizing the surface energy at the wall by detaching the vapor from the wall. After this has been accomplished the only remaining surface energy to be minimized, is the surface energy between liquid hydrogen and its vapor. The most effective way to do this is to have a single vapor bubble in the tank with the smallest possible surface area, i.e., a sphere. In Reference 17, Dr. Ta Li of General Dynamics/Astronautics mathematically derived the equation of a sphere as the most stable configuration for hydrogen vapor in a zero-g environment.

When the volume of liquid hydrogen has dropped to a point where the sperical volume of the gas ullage space is larger than the smallest dimension of the tank, a sphere is no longer possible. As the ullage volume increases beyond the maximum spherical volume possible, the liquid will first wet the wall, then fill the cavities and form a central ullage wherein the bulk liquid is distributed in such a manner that the surfaces backed by bulk liquid are of uniform curvature. Other surfaces will be film-wetted tank walls. The escaping tendency from the wetted tank walls will be adjusted by evaporation (thus reducing the thickness) to equal the escaping tendency from the curved surfaces. Thus the escaping tendency of the surfaces exposed to the vapor volume will be uniform, and the pressure in the vapor will be uniform. If more than one configuration is possible, the one or ones with the smallest amount of liquid vapor surface area will prevail. The bulk liquid surface will become tangent to the film wet surface in a transition region. The curvature of a bulk liquid surface will be greater than, or equal to, the curvature of any exposed film wet surface (otherwise the liquid will collect on the film wet surface).

The discussion has so far dealt with the final equilibrium fluid configuration. Depending upon mechanical and thermal disturbances, equilibrium may be attained slowly or rapidly. For instance, if Centaur at engine cut-off is put into zero-g with no mechanical disturbances, the liquid-gas interface will initially form an inverted hemisphere. The remaining tank walls will be covered with only a molecular layer of liquid hydrogen. Eventually the liquid hydrogen will flow up the cylindrical tank walls and form another hemispherical cap at the forward bulkhead. Figure 2 shows the initial hydrogen configuration at zero-g if no mechanical disturbances were present at engine cut off and the final equilibrium hydrogen configuration at zero-g for Centaur.

To investigate fluid behavior in transient, i.e., fluid motion caused by a non-equilibrium condition or due to external disturbances, the hydro mechanical forces of significance must be established. The usual method of exploring the relative importance of these forces in determining the resulting fluid motion is to express ratios of two or more forces as non-dimensional parameters. The parameters of importance for investigating Centaur propellant behavior while in a low or zero-g environment were as follows:

(1) $\frac{\text{Inertial force}}{\text{Cohesive force}} = \frac{\rho V^2 L}{\sigma_{LG}}$ (Weber Number, W_e)

(2) $\frac{\text{Gravitational force}}{\text{Cohesive force}} = \frac{\rho L^2 g}{\sigma_{LG}}$ (Bond Number, B_o)

(3) $\frac{\text{Inertial force}}{\text{Gravitational force}} = \frac{V^2}{gL}$ (Froude Number, F_n)

(4) $\frac{\text{Inertial force}}{\text{Viscous force}} = \frac{\rho VL}{\mu}$ (Reynolds Number, R_e)

All these parameters involve the system geometry such as characteristics dimension L, flow velocity V, and acceleration g. There is also a dependence on fluid properties; density, ρ , viscosity, μ , and surface tension, σ_{LG}.

It was thought that fluid motion during zero-g was primarily dependent on the Weber number. However, recently the results of zero-g liquid behavior tests Reference 36, conducted at NASA Lewis Research Center, have indicated that the process of liquid flow toward an equilibrium condition may be too complex to be described by this parameter. During the NASA Lewis tests, liquid was contained in various size glass spheres and its advancement along the spheres versus zero-g time determined. The data given in Figure 34 of the reference was replotted in Figure 3 of this report using different coordinates. The predicted slope of the family of curves is

1.5; the actual slopes varied between 1.22 and 1.42. This variance in the slopes indicates that a different similiarity function could possibly exist. The surface energy of the system is based on liquid-gas, liquid-solid, and gas-solid surface energies. In general, only the liquid-gas surface energy is known. It has been assumed that the driving force, i.e. the force which determines the rate of advancement, was a function of the liquid-gas surface energy or surface tension. It may be that other surface energy terms influence the rate of liquid flow, and therefore, the Weber number based on the liquid-gas surface tension would not be the appropriate parameter. Until this apparent lack of scaling knowledge can be assessed, considerable care should be used in extrapolating zero-g model test results to Centaur. However, time scaling derived from the Weber number for particular tests could possibly be justified. For example, it is felt that this parameter may be correct for scaling the results of the zero-g outflow tests. There may be a very important difference between predicting liquid flow as it approaches a minimum energy distribution and predicting the time for gas pull through to occur under outflow conditions. This is discussed further in Section III-B of this report.

In Reference 1 experimental data is presented to corroborate the Weber number for a simple system; i.e., globules of one liquid oscillating in a large amount of another. It should be noted that this may be very different than the case where the liquid-solid and gas-solid energies could possibly be an important factor. Liquid-liquid models with water globules in a mixture of Freon TF and Stoddard solvent, and kerosene globules in a mixture of water and methyl alcohol were used. The periods of oscillation of the bubble versus the globule diameters were plotted and the slopes measured. The measured slopes were within $\pm$ 2% of the value 1.50, predicted by the Weber number. Although these tests results were confined to a simple system, they did lend support to the orientation tests where the fluid behavior observed during these experiments appeared to be similar to the fluid response during the orientation maneuvers.

B. Experimental Approach

At the time the program was initiated, the three experimental methods proposed for investigating the effects of zero-g were the linear drop tower, the aircraft and ballistic missile. Each technique, in order, would extend the zero-g times available for testing. All these approaches were used and in addition, a fourth method, using liquid-liquid models, was developed during the program.

1. Laboratory Tests

a. Linear Drop Test

The first method used to obtain zero-g at General Dynamics/ Astronautics was the linear drop test tower. The early tower was 16 feet in height and allowed approximately 1 second of zero-g. Later in the program a 2-second facility was built (64 feet). The primary advantages of this method were that meaningful data could be obtained inexpensively and tests results were readily repeatable because of the ease in controlling the initial test conditions.

However, practical considerations limited the free fall duration to 1 or 2 seconds since the height of free fall varies as the square of the drop time. Zero-g equilibrium conditions could not be attained in the short period of time unless very small models were used. A further disadvantage of the drop tower was the difficulty in streamlining the test capsules such that the influence of air drag would be negligible.

b. Liquid-Liquid Models

During the zero-g test program, a method was devised to simulate the equilibrium zero-g configuration of the liquid and gaseous hydrogen in the Centaur tanks. This simulation was produced by two immiscible liquids, of the same density, in a transparent model container shaped like the full scale Centaur fuel tank. The liquids were basically oil and water and were adjusted to have the same density by small additions of a heavy or light component to the oil or water as required.

As in the Centaur fuel tank, the two fluids in the model had an interface whose surface tension was the same throughout. Gravity had the same effect on the two fluids and, therefore, had no effect on their relative configuration or position. One of the fluids wet the container structure so readily that the angle of contact of the interface with the wall was essentially zero. The other liquid did not wet the container walls. The great advantage of these models was that the equilibrium configuration could be easily demonstrated for the basic tank configuration and for complex configurations of the Centaur liquid hydrogen and liquid oxygen tanks. The use of the models, however, was primarily limited to static zero-g demonstrations and only in special cases could they be used for dynamic applications. Figure 4 is a photograph of a liquid-liquid model. A more detailed description of these models is contained in Reference 2.

2. Aircraft Tests

Preliminary testing in the latter part of 1959 and early 1960 on an Air Force C131B aircraft had demonstrated the feasibility of using an aircraft as a zero-g test facility. The C131B was theoretically capable of 15 seconds of zero-g time. In June of 1960, a KC135 aircraft was made available to General Dynamics/Astronautics by the Air Force for zero-g testing. This aircraft was theoretically capable of 30 seconds of weightlessness. The sequences required to obtain the zero-g condition on the KC135 were as follows:

(a) The KC135 was placed in a shallow dive of approximately 5° at 24,000 ft.

(b) At a pre-determined velocity, or Mach number (approximately 0.9) the aircraft was gradually pitched up to an angle of climb of about 50°.

(c) The angle of climb was then gradually decreased so that the aircraft followed a parabolic path until the initial Mach number was again attained.

The advantage of the aircraft experiments was the longer zero-g time obtainable for the tests. The greater expense and inaccuracies in the flight trajectory due to pilot errors and wind gusts at altitude represented major disadvantages.

3. Aerobee Missile Tests

The test dewar of the Aerobee was a 9-inch diameter sphere with a .010-inch thick stainless steel wall. This was centrally supported in a 11-inch diameter outer sphere with a .030-inch thick stainless steel wall. The space between spheres was evacuated to .10 microns. An electric heater was mounted in the vacuum space on a 10-inch diameter copper sphere with a wall thickness of .030 inches. A temperature regulator modulated the heater current to maintain the heat shell at a predetermined temperature. This assembly was mounted in the forward section of the Aerobee missile. For all the General Dynamics/Astronautics tests, liquid hydrogen was used as the test fluid.

ZERO-G CONFIGURATION OF LIQUID HYDROGEN IN CENTAUR

Initial hydrogen configuration at zero-g, if no mechanical disturbances are present at engine cutoff.

Final equilibrium hydrogen configuration at zero-g.

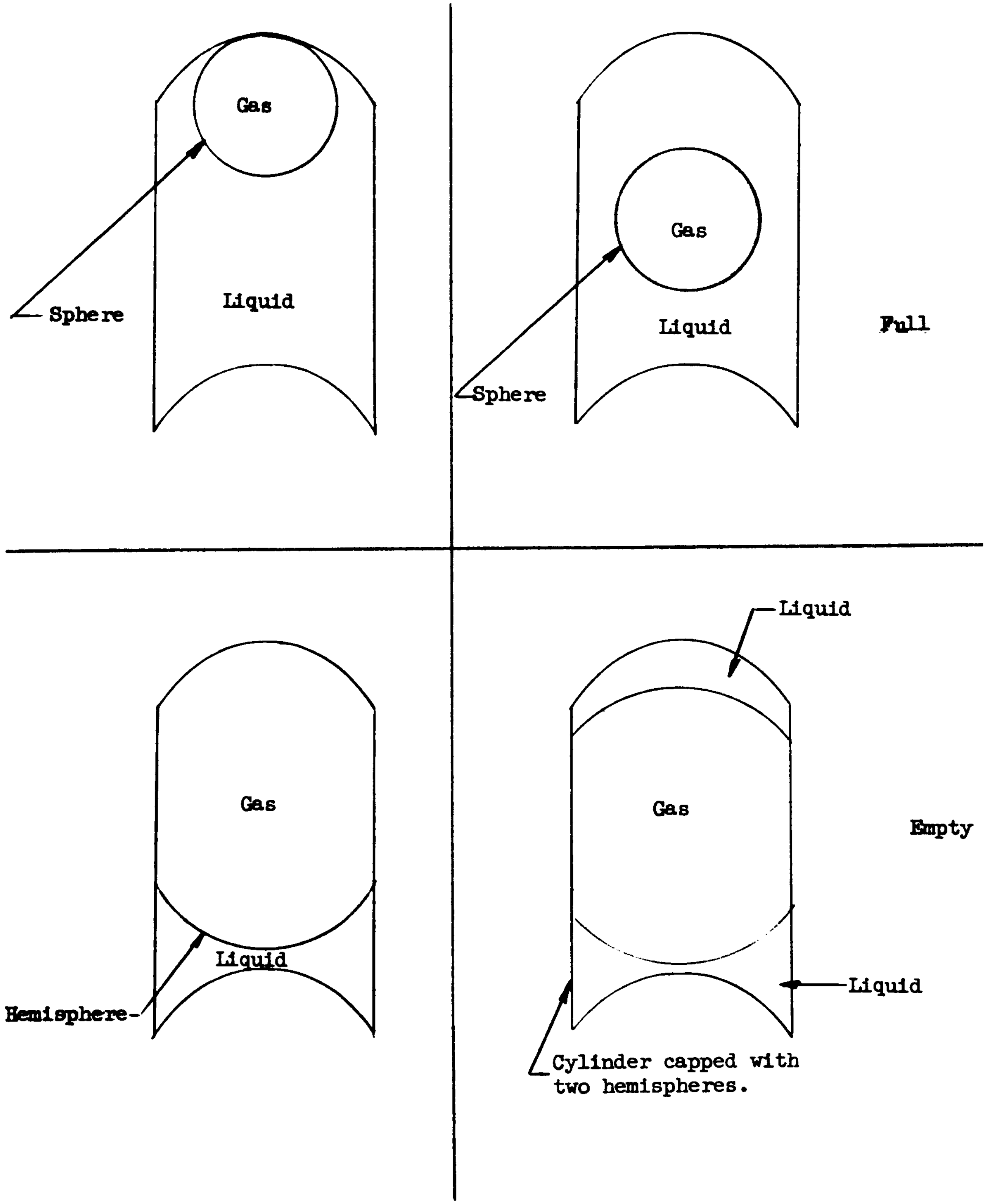
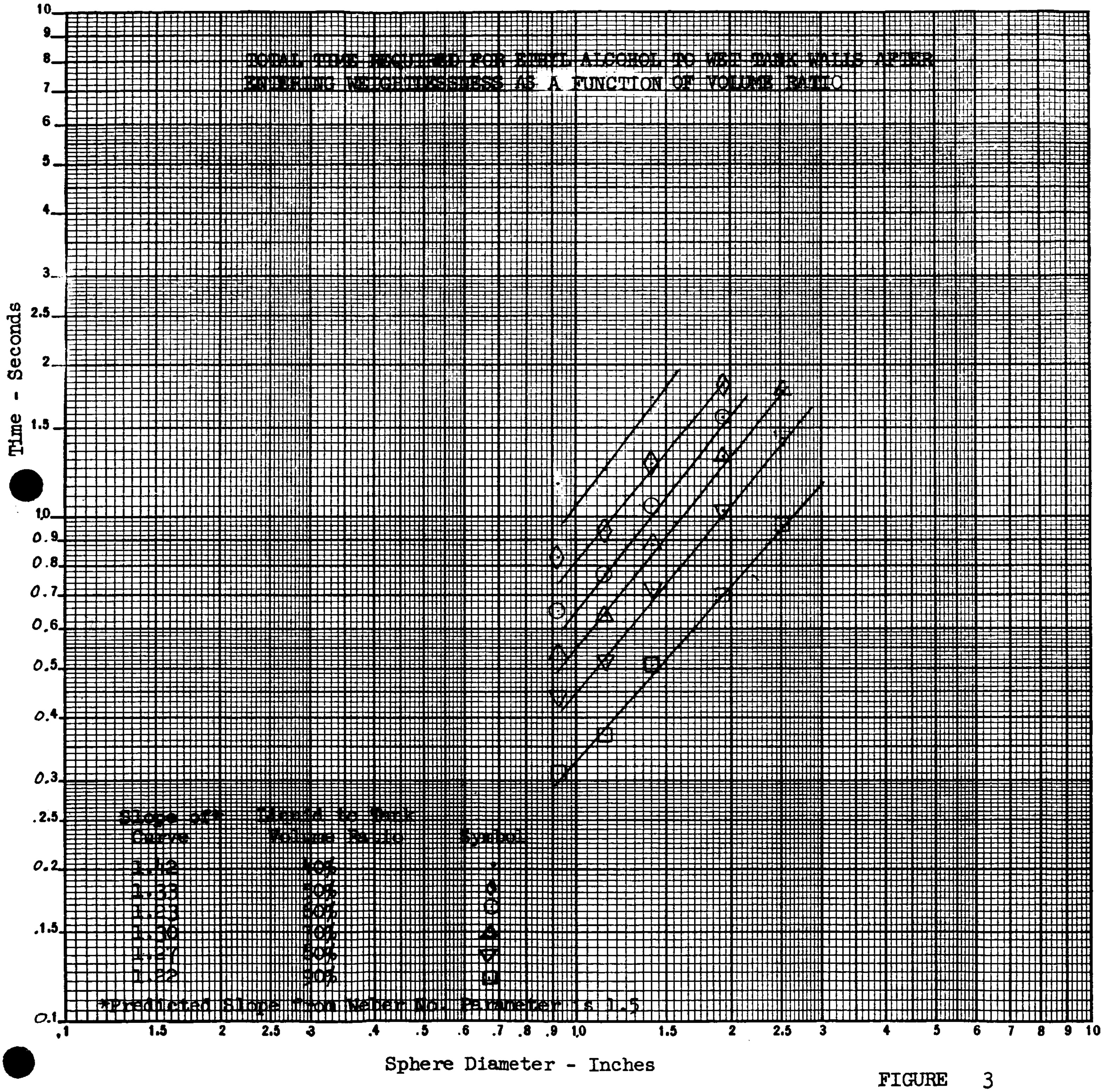


FIGURE 2



AS A FUNCTION OF VOLUME RATIO
Slope of*
Curve
Volume Ratio
Symbol
1.33
1.30
90%
*Predicted Slope from Weber No. Parameter is 1.5
Time - Seconds
Sphere Diameter - Inches

FIGURE 3

CENTAUR LIQUID-LIQUID MODEL

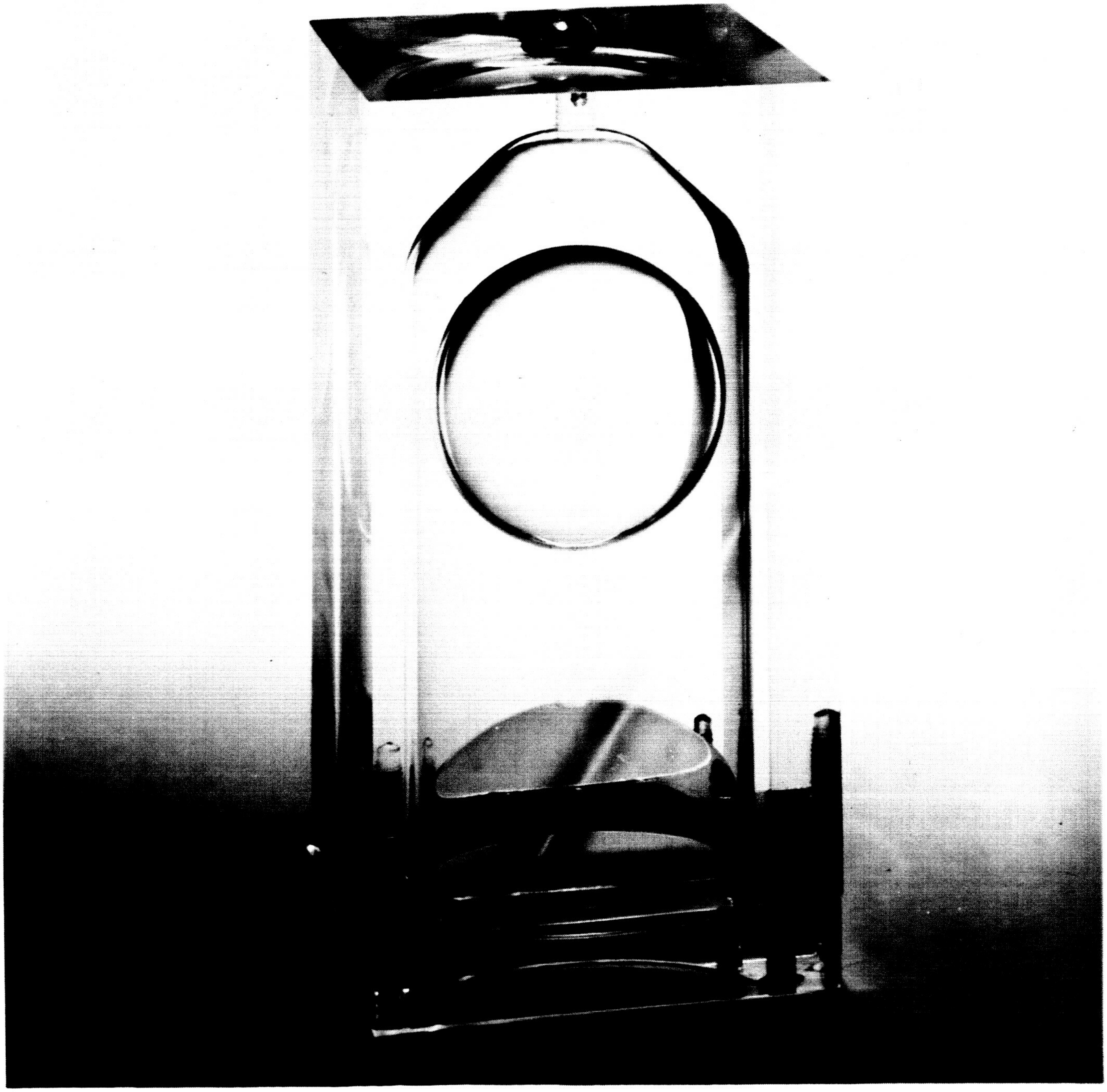


FIGURE 4

II. FLIGHT TEST DEVELOPMENT

A great deal of effort was expended early in the test program to develop apparatus and techniques to allow safe and useful zero-g testing with liquid hydrogen. The details of the flight test development are described in Reference 3. Developmental efforts were concentrated in two areas: development of a "free floating" technique for the test capsules, and the fabrication of a safety kit system to provide an inert atmosphere for testing with liquid hydrogen.

A. Development of "Free Floating" Technique

To obtain reliable and useable data from these tests, it was considered essential that the test package, located in the aft compartment of the aircraft, be in a zero-g environment for as long a period of time as possible. Therefore, early in the program considerable testing was performed to develop a technique to "free float" the test capsules. The preliminary zero-g tests which were performed in 1959 and the early part of 1960 on the C131B had demonstrated the importance of developing a method of floating the test capsules where they would not be exposed to any accelerations. The first test packages on the C131B were bolted to the aircraft. However, in spite of the skilled piloting of the aircraft, small residual "g" forces were always present which considerably affected the test results. Initial efforts to develop a "free floating" technique on the C131B consisted of an instrumented experiment suspended by strong cords within a cagelike structure. Testing showed that this arrangement was capable of giving better zero-g conditions than possible with the bolted-to-the airplane configuration. However, the elasticity in the suspension cords stored considerable energy during the 2-1/2 g pullup and this energy was released to the package during the onset of zero-g.

In June of 1960, when the flights were initiated on the Air Force KC135 aircraft by Aeronautical Systems Division and General Dynamics/ Astronautics personnel, an attempt was made to further develop the "free floating" technique. Approximately 35 flights were performed to investigate the best methods for obtaining longer useable zero-g periods. An entirely free capsule was used. Essentially the technique involved flying the aircraft around the test package. To aid the pilot in flying the maneuver, sensitive accelerometer gages were mounted on the instrument panels in front of the pilot and co-pilot to indicate both longitudinal and vertical accelerations. A Kin Tel closed circuit television system was installed to aid the pilot in seeing the location of the test equipment with respect to the aircraft surfaces in the aft compartment. A 5-inch monitor was mounted on the instrument panel in front of the pilot. The pilot then made corrections by using the TV to determine direction of correction and by cross referencing the accelerometer gages to determine magnitude of correction needed. A third pilot aid was verbal commands given by an observer in the aft compartment. The success of this aid depended upon the ability of the "talker" to accurately describe instantaneously the capsule position and velocity. With this technique, useable zero-g times of between 9 and 15 seconds were obtained one out of every three trajectories. It should be pointed out that pilot skill was not the only factor which prevented an extension of zero-g times with the "free floating" technique. An additional factor which influenced the success of all phases of the test program was air turbulence encountered between 24,000 and 35,000 feet. The air turbulence at this altitude is a function of both wind velocity and wind shear. Wind difference velocities of 20 to 25 knots began to cause aircraft perturbations, particularly at wind velocities above 40 knots. Although for most testing purposes these wind velocities are considered negligible, they were of a sufficient magnitude during zero-g testing to limit the useable zero-g time obtainable on the aircraft.

As part of the development of the "free floating" technique, methods of releasing the test capsule into a zero-g environment were also investigated. The float-off-the floor method was attempted first. Here the capsule lifted off at the first negative acceleration and then the pilot, in theory, simply flew the aircraft around the test capsule. To do this, the pilot was required to approach zero-g almost perfectly, with little overshoot, or the capsule would fall quickly against the ceiling. For this reason, the method never produced satisfactory results. The next method tried was to have the package held by a crew member in the center of the cabin until the pilot had overcome the initial, major overshoots in acceleration. The capsule was then released at the pilots command. This technique was moderately successful.

The third and best method used a table which could be collapsed by the pull of a lanyard and which was of a height to put the package at the cabin center. The table was collapsed at the pilot's command. All these techniques suffered a common problem. As the normal acceleration approached zero the vibration and small variations from the desired path had an increasing effect on the liquid in the capsule, and often considerable agitation of the test liquid was produced.

B. Aircraft Test Safety System

For safety reasons, a system was fabricated and installed on the KC135 aircraft to provide an inert nitrogen atmosphere for testing with liquid hydrogen. The central feature of the liquid hydrogen flight test system was a test cell fabricated from nylon woven cloth impregnated with neoprene rubber with an inflated volume of approximately 1300 cubic feet. During testing with liquid hydrogen, the test cell, located in the aft compartment of the aircraft, was pressurized with nitrogen gas to provide an inert environment. The construction of the bag (stainless steel floor and walls painted with conductive silver paint) provided an environment with small chance of any static discharges. Pressurization was provided by a nitrogen converter system consisting of the liquid nitrogen storage dewar pack, boiler and superheater. The boiler evaporated the liquid nitrogen fed in from the storage pack, and the superheater warmed the cold gas prior to introduction into the test bag. The test cell pressure was maintained at approximately 1-inch H_2O above cabin pressure at all times. Pressure relief was accomplished by a relief valve venting directly overboard. In case of too high pressure in the bag, due to mistakes in system operation, sudden changes in cabin pressure or breakage of a test dewar, a rupture diaphragm and appendage bag were connected to the aft section of the test cell. The appendage bag had an inflated volume of 2000 cubic feet and the system diaphragm was set at 1.75-inches H_2O.

The liquid hydrogen was stored in a sealed dewar. The hydrogen boil-off from the storage dewar and test capsule was vented overboard at all times.

Gas analyzers were used to monitor the amount of oxygen and hydrogen content when the test cell was being used for liquid hydrogen testing. According to Reference 37 , hydrogen is combustible in air over the range of about 4% to 74%. Even a mixture of 89% nitrogen, 6% hydrogen and 5% oxygen was considered theoretically combustible. Limiting the hydrogen concentration to 4% (gas plus the potential gas in the capsule dewar) in the bag would have held the initial liquid hydrogen fill to 2.2 liters. Because this limit was so low, some simple tests were performed to find the practical gaseous hydrogen limit. During one test, exhaled breath was blown into a container with known mixtures of hydrogen and nitrogen. A second test (simulating a bag leak) ignited hydrogen and nitrogen mixtures in air. The results of these tests showed that a 10% hydrogen gas concentration was acceptable. This was equivalent to about 4.6 liters of liquid hydrogen (a full dewar). The oxygen limit in the bag was set at 2% which was well below the recommendation of Reference 38.

Since most tests did not use a full dewar, a chart was prepared to show the maximum safe quantity of liquid hydrogen which could be allowed at any value of gaseous hydrogen concentration in the bag. In the event that the gaseous hydrogen concentration was too high, the bag was partially collapsed and then refilled with gaseous nitrogen.

Operation of the test cell and associated equipment was thoroughly tested on the ground and in flight using liquid nitrogen prior to testing with liquid hydrogen. Six complete simulated missions were completed in an airplane mock up at General Dynamics/Astronautics using liquid hydrogen before the system was accepted and installed on the aircraft. After installation of the safety kit system on board the aircraft, several flights were completed with liquid nitrogen prior to starting the testing with liquid hydrogen. In addition, prior to each new liquid hydrogen test series, flights were performed to demonstrate satisfactory system operation.

The difficulties encountered in fabricating a system for making safe zero-g tests in an airplane with liquid hydrogen as the working fluid delayed the test program approximately six months. It was recognized that the completed system could not be made fool proof. For example, it was conceivable, though unlikely, that the bag might rupture, the liquid hydrogen spill, and an ignition source occur simultaneously. This concentration was simply accepted as one of the hazards of the tests. However, every violation which could be anticipated was examined in detail. Possible failures of the equipment and personnel were taken into consideration in the design and testing of the system, in the preparation and development of the test procedures, and in the selection and training of the test personnel.

III. LIQUID BEHAVIOR TESTS

Prior to the initiation of the zero-g program, little information existed as to whether, during Centaur coast periods, the cryogenic liquids would be dispersed in the form of a fog, in droplets or in a single mass. For long periods of zero-g, it was not known whether the liquid would wet and cling to the container, leaving only gas in the center, or whether it would collect in the center with the gas adjacent to the container walls. It was recognized that the state of the liquid would affect all phases of Centaur vehicle operation. Boil-off rates, venting of the fuel tank, hydrogen peroxide consumption, and propellant settling are directly dependent upon the behavior of the liquids.

Tests were therefore accomplished to determine the behavior of liquid hydrogen and liquid oxygen at the beginning of, during, and following periods of zero-gravity. Liquid behavior studies included the following portions of the Centaur flight:

A. Coast Periods

B. Propellant Settling and Outflow

C. Vehicle Orientation and Re-orientation

A. Coast Periods

Knowledge of the equilibrium configuration of the liquids during a Centaur coast period was a necessary first step to considering the effects of disturbances on the liquid. As discussed in Section I-A, it is possible to theoretically predict the equilibrium zero-g configuration of the liquid and gaseous hydrogen in the Centaur tanks from the principal of minimum energy. However, this is a formidable task for even a simple configuration. The development of the liquid-liquid models demonstrated precisely the central ullage configuration which had been computed and indicated in drop and aircraft tests. Furthermore, for more complex configurations of the fuel tank, the liquid-liquid models again demonstrated the shape of the ullage, but as modified by ullage support structures, center vent and instrumentation probes.

The original intent in the investigation of an ullage support structure was to develop a control surface that would eliminate the need for the hydrogen peroxide settling rockets in Centaur prior to an engine re-start. The elimination of the settling rockets would represent a possible payload gain due to the conservation of hydrogen peroxide. The liquid-liquid models had demonstrated that an ullage support structure could exert small but positive forces on the ullage bubble to move it to any desired location in the fuel tank. Therefore, it was considered possible that in Centaur an ullage support structure could be used to concentrate more liquid in the vicinity of the boost pump outlet. Thus, during the chilldown and main engine start sequence the requirements for a continuous liquid flow would be satisfied.

The selection of a control surface for the Centaur fuel tank was based on the following design considerations:

(1) A minimum weight surface. The weight of such a surface should not be greater than the payload gain due to conserving hydrogen peroxide.

(2) A surface which would minimize the size of bubbles caused by heat transfer and shorten the time required for bubbles to merge with the ullage.

Both cylindrical and conical surfaces were investigated. The advantage of the conical shape over a cylindrical shape is that bubbles will be forced away from the intermediate bulkhead as they grow. Since the primary objective of an ullage support structure was to concentrate liquid in the vicinity of the boost pump outlet, a 1/4 section of a right truncated cone was designed and installed near the boost pump of one of the first Centaur vehicles. Model zero-g outflow tests were performed with this surface and are discussed in Section III-B. The tests resulted in removing the ullage support structure from the Centaur because the surface did not serve the purpose for which it was intended. A control surface for the liquid oxygen tank was not designed because a thrust ring, installed for structural purposes, served the same function.

It was demonstrated, first with liquid-liquid models and then analytically, that liquid would wet only a small portion of a tube inserted into the ullage bubble while in zero-g. This observation made the feasibility of a center vent tube more attractive because liquid losses due to flow along the tube would be essentially zero. Furthermore, the liquid vapor sensors mounted on a "Christmas Tree" like structure in the Centaur fuel tank would not be adversely affected by liquid "creep" during a coast period.

B. Propellant Settling and Outflow

Following a re-orientation maneuver and prior to an engine re-start, the main engine pumps must be chilled down to their respective liquid temperatures to prevent vapor flow at engine start. The present method for achieving chilldown is to first fire four 50 lb thrust rockets to "settle" the propellants, then open valves which will allow liquid to flow through the pumps for a specified period, thereby chilling the pumps. The purpose of the rockets is to settle the propellants at the aft end of both the hydrogen and oxygen tanks, after a Centaur coast period. This is necessary to assure that liquid will be present at the boost pump inlet at initiation of chilldown flow rates. However, it is possible that the heat transfer effects or liquid sloshing could cause large quantitites of vapor flow through the pumps during chill-down or engine start, and a failure might occur. Therefore, it was considered necessary to conduct model tests to determine what the distribution would be and if successful engine starts would occur in flight.

Testing was performed in two areas. Initial tests were conducted for the idealized condition of no liquid sloshing or vapor entrainment during outflow. These test results were optimistic and represented the maximum time for flow to satisfactorily continue before failure due to gas pull-through would occur. The second series of tests simulated as closely as possible the actual condition of propellant setting followed by outflow (vapor entrainment created by heat transfer could not be included).

1. Outflow Tests

The outflow tests were performed to determine if scheduled pre-start sequences would result in satisfactory main engine starts and to investigate the possibility of performing starts using fewer than four settling rockets. The test criteria was to determine the time required for gas pull-through to occur. Gas pull-through is produced when the liquid flow inertial forces created by outflow overcome the forces which tend to maintain a normal liquid-gas interface. A planar surface is maintained in a gravitational field, and a curved interface is maintained by surface tension forces in a zero-g field. Pull-through becomes eminent as the interface approaches the tank outlet because inertial forces are a function of liquid velocity, which rapidly increases near the outlet. Thus, as the liquid level is reduced, the interface deforms until pull-through occurs.

Prior to model testing, the governing parameters were determined and are discussed in detail in Reference 4 . With the settling rockets firing, acceleration and inertial forces will control the fluid behavior during outflow. These forces are the fluid flow parameters described as the Froude number. Viscous forces were eliminated on the basis that they are important only near a solid surface where large velocity gradients may exist. If outflow is attempted without firing the settling rockets, it was thought that only surface tension and viscous forces would exist to oppose liquid inertial forces. An order of magnitude analysis again showed that viscous forces were negligible, and the fluid parameter described as the Weber number was selected to simulate Centaur liquid behavior during zero-g outflow. The time for pull-through to occur in the Centaur was found from the observed time of the model tests which was then applied to the following equations:

$$\frac{t_c}{t_m} = \sqrt{\frac{D_{o_c}}{D_{o_m}} \quad \frac{g_m}{g_c}} \qquad \text{(From Froude Number)}$$

$$\frac{t_c}{t_m} \quad \sqrt{\frac{\rho_c}{\rho_m} \left(\frac{D_{o_c}}{D_{o_m}}\right)^3 \frac{\sigma_m}{\sigma_c}} \qquad \text{(From Weber Number)}$$

where:

t = time

D_o = characteristic length

g = acceleration field

ρ = liquid density

σ = liquid-gas surface tension

Subscripts c and m refer to Centaur and model. The equations are developed in the Appendix of Reference 4 . The time scaling derived from the Froude number was verified over a tank model size of about 5 to 1. It is felt that extrapolation to Centaur conditions is justified based on this excellent correlation. The time scaling derived from the Weber number for zero-g outflow was verified for limited outflow conditions in a 1/35th scale model and therefore may be subject to error when extrapolated to the Centaur outflow conditions. However, because the outflow process appears to depend only on the liquid-gas surface energy, it was thought that the Weber number parameter could be used for this application with a good degree of confidence.

Both liquid-gas and liquid-liquid model tests were conducted to simulate the scheduled pre-start sequence and reduced "G" tests. The primary reason for liquid-liquid tests was to obtain higher Froude numbers than could be obtained in the liquid-gas tests. 1/20th and 1/35th scale model plexiglas containers were used and motion picture coverage obtained for all tests. Liquid-gas tests included water, Freon TF, or Stoddard solvent, with air. Liquid-liquid tests were conducted with two immiscible liquids, Freon TF and water. Freon TF was the liquid, and water, which is lighter than freon, the simulated "gas".

Liquid-gas tests using Freon TF and Stoddard solvent were performed in the drop tower apparatus to simulate childown during zero-g. It was not possible to establish initial liquid distributions similar to those expected in Centaur at the beginning of the second and third pre-start. The equilibrium distribution will be modified by heat transfer and the re-orientation maneuver prior to the pre-start sequence, and most likely will result in less than the full amount of liquid to be concentrated at the intermediate bulkhead. The reduced liquid mass at the bulkhead will cause the interface to be nearer the boost pump inlets, which will result in a shorter pull-through time than was determined from tests. During the model tests, most of the liquid was located at the intermediate bulkhead of the hydrogen tank and at the bottom of the oxygen tank, because sufficient zero-g time was not available to attain the equilibrium distribution and then perform the test. Heat transfer and re-orientation maneuvers will have no effect on the first pre-start sequence because the vehicle need only separate a prescribed distance from the booster before pre-start can begin. The tests were performed with and without an ullage support structure, and the results were compared in order to determine the effectiveness of the structure to delay the time for gas pull-through to occur in the hydrogen tank.

The results of the simulated scheduled pre-start sequence and reduce "G" tests are presented in Tables I and II and are summarized as follows:

(a) Pull-through will not occur for any of the pre-start sequences in the liquid oxygen and liquid-hydrogen tanks if the planned four settling rockets are fired continuously during chilldown and main engine start.

(b) Pull-through will not occur in the liquid oxygen tank during any of the three pre-start sequences if only two rockets are fired.

(c) Pull-through will not occur during the first and second pre-start sequence in the liquid hydrogen tank if only two rockets are fired.

(d) Pull-through could possibly occur in the liquid hydrogen tank during the third pre-start sequence if only two rockets are fired, considering the tests were performed under ideal conditions.

Tests simulating the first pre-start were not conducted because extrapolation from the other tests indicated no problems would occur.

Test results of the zero-g pre-start sequence is shown in Table III, and summarized as follows:

(a) Pull-through will not occur in the liquid oxygen tank.

(b) Pull-through will not occur during the first pre-start in the liquid hydrogen tank and could possibly occur during the second pre-start.

(c) Pull-through in the liquid hydrogen tank will occur during the third pre-start.

(d) The ullage support structure designed for the hydrogen tank is of little help in delaying or preventing pull-through.

The ullage support structure was ineffective because the surface tension forces were considerably smaller than liquid inertial forces. The effectiveness of a control surface for the Centaur fuel tank could be improved by increasing the size and thus maintaining the liquid interface even further from the boost pump inlet. This distance would reduce liquid inertial forces such that surface tension forces could prevent pull-through. However, the weight of such a structure would be greater than the payload gain due to conserving hydrogen peroxide. Therefore, for Centaur there appears to be no advantage in using an ullage support structure.

2. Settling-Outflow Tests

The purpose of this test series was to simulate as closely as possible the actual condition of propellant settling, sloshing and sloshing outflow. Vapor entrapment caused by heat transfer effects could not be simulated. Liquid oxygen model tests were not conducted during this phase of the test series because fuel conditions would be more severe.

Simulation of Centaur fluid conditions could not be completely satisfied during the model tests. Such a condition has yet to be observed, and therefore, cannot be duplicated. However, based on present knowledge, two extreme conditions were considered possible; the distribution created by the zero-g separator operation, and an equilibrium zero-g distribution. Only the latter could be simulated during the model tests. According to the best estimates, liquid will flow down the tank walls when the settling rockets are turned on.

An analysis was performed to determine the governing model test parameters. For the settling simulation, it was shown that viscous or form drag forces would be small compared to the acceleration force. Surface tension effects were also negligible for the settling simulation. Therefore, the significant parameter was the Froude number. By illustrating that acceleration forces would predominate, simulation of propellant settling could be achieved with any scale model tank as long as viscous and surface tension forces remained small. This assertion is proven in Reference 4.

An order of magnitude analysis showed that surface tension forces would be negligible during simulation of liquid sloshing. Because only a relatively short time period of sloshing was of interest, little damping should occur and viscosity effects could also be ignored. Therefore, once again the Froude number was the governing test parameter. As long as settling is simulated, the model test Froude number for sloshing simulation will also be equal to the Centaur Froude number.

It was previously demonstrated that outflow could be simulated if the proper model test Froude number was selected. Hence the entire pre-start sequence could be simulated from the beginning of settling until the end of childown.

An 18-inch diameter aluminum model fuel tank was used during testing. The standard forward bulkhead was removed and a reservoir installed to contain some of the test fluid above the intermediate bulkhead. Liquid was released from the reservoir, and at a predetermined time, a valve downstream of the boost pump inlet opened, commencing flow. Motion picture coverage of the plexiglass boost pump inlet was used to indicate the time for pull-through to occur.

Preliminary outflow tests were conducted with no prior settling to establish an ideal reference time for pull-through to occur. Each test condition was conducted using as a variable the time period between liquid being bottomed and start of outflow. This was to simulate increased settling rocket firing time for reducing sloshing and enabling entrapped vapor to escape the boost pump region prior to the start of flow. The purpose was to determine the effect of increased settling time upon gas pull-through time.

If the Centaur separator has not operated for a time prior to the settling period, approximately one-half of the liquid will be located at the intermediate bulkhead, following a Centaur re-orientation maneuver. Therefore, to simulate this condition, tests were conducted with the liquids evenly distributed between the reservoir and bulkhead. Testing was also performed with all the liquid in the reservoir to determine if sloshing and outflow would be appreciably affected.

The test results are presented in Tables IV, and V and summarized as follows:

(a) Considerable gas entrapment occurred during propellant settling resulting in:

(1) About 35% - 50% gas flow by volume at the start of childown for all test conditions.

(2) 2% - 5% gas flow at what would be the end of Centaur childown. The percent of vapor was extremely difficult to estimate because the bubbles were small and finely dispersed.

(b) The time for clear flow to be established appeared to be dependent on the duration of acceleration field influence on the entrapped vapor.

(1) Delaying the start of outflow did not reduce the duration of vapor outflow. Representative test results converted to Centaur times are shown in Table IV.

(2) The liquid currents, established when the liquid was settled, appeared to be sufficiently strong to impede bubble rise in the acceleration field.

(c) For the conditions where 100% of the liquid was contained in the reservoirs approximately 80% more time was required for clear flow to occur than when only 50% of the liquid was originally in the reservoir.

(d) Main gas pull-through during outflow was not appreciably affected by gas entrapment and sloshing. A comparison is given in Table V.

It is expected that the quantity of vapor entrapped by the liquid hydrogen flow stream will be primarily dependent upon the effectiveness of accelerations to clear the boost pump region of vapor prior to commencing outflow. Once outflow has commenced, a liquid velocity toward the pump will be established and is greater than the bubble rise velocity. A correlation of bubble rise rates in a variety of liquids is presented in Reference 39. The test correlation obtained was a simple plot of drag coefficients versus Reynolds number. The maximum bubble rise velocity was then computed for gaseous hydrogen in liquid hydrogen at low accelerations, assuming the buoyant force of the bubble was equal to the drag force on the bubble. These results are shown in Figure 5. This curve shows that the maximum bubble velocity with four rockets firing is 40% greater than with two rockets firing. Therefore, approximately 100% more propellant would be consumed. However, more efficient use will be made of the rocket propellant if two rockets are fired while liquid hydrogen is being cleared of vapor.

Based on the results of the outflow and settling outflow tests, the following changes are recommended for the Centaur pre-start sequences:

(a) Perform the first pre-start sequence without firing the settling rockets.

(b) Perform the second pre-start sequence firing only two of four settling rockets.

(c) To settle the propellants prior to the 3rd pre-start sequence, fire two rockets. Fire all four rockets at the start of chilldown flow.

C. Orientation Tests

Part of the liquid behavior test program was an investigation of the liquid disturbances caused by the Centaur orientation and re-orientation maneuvers. Since the vehicle must be oriented to the sun following an engine firing and re-oriented in the proper velocity vector prior to an engine re-start, these maneuvers were investigated to find if fluid disturbances would be sufficient to affect center vent operation. Operation of the vent is based on the assumption that the liquid hydrogen will not be in the form of droplets flowing throughout the tank during the zero-g coast.

The sequence performed to orient and re-orient the vehicle is as follows:

(1) The vehicle is rolled in one plane to achieve the desired attitude.

(2) A combination of the 50 pound ullage rockets and the attitude control rockets are fired intermittently to produce an angular and linear acceleration.

(3) This acceleration period is followed by a period of constant rotation rate, the length of which is determined by the required orientation angle.

(4) The deceleration period is the reverse of the acceleration period.

Since the angular velocity is approximately one degree/second, the maximum turn time is about 180 seconds. The angular velocities are exactly cancelled but the linear velocities, (i.e. the velocity increments), are not cancelled.

Prior to testing, the governing parameters were established. The parameters affecting the oscillatory response of a liquid in a container in a zero-g environment are the density, surface tension, viscosity and characteristic dimension. For purposes of these tests, viscous forces were eliminated on the basis that several complete oscillations could be observed whenever a zero-g equilibrium ullage shape was disturbed. Therefore, with such low damping, the natural period of oscillation was essentially independent of viscosity. Furthermore, the orientation maneuvers were completed in a fraction of a zero-g ullage oscillation. Because viscous forces were negligible, the fluid parameter described as the Weber number was selected to simulate the oscillatory response of the Centaur liquid hydrogen. The following equation was written to represent the relation of model time, T_m, to Centaur time, T_c.

$$\frac{T_m}{T_c} = \sqrt{\frac{(\rho/\sigma)_m}{(\rho/\sigma)_c}\left(\frac{D_m}{D_c}\right)^3}$$

where:

t = time

D = characteristic length

ρ = liquid density

σ = liquid-gas surface tension

Subscripts c and m refer to model and Centaur. During the acceleration part of the orientation and re-orientation maneuvers, the following equation was used to scale model to full size effects.

$$\frac{A_m}{A_c} = \frac{(\rho/\sigma)_c}{(\rho/\sigma)_m} \left(\frac{D_c}{D_m}\right)^2$$

where:

A = acceleration

ρ = liquid density

σ = liquid-gas surface tension

D = characteristic dimension

Subscripts c and m refer to Centaur and model. This relationship was obtained by dividing the Weber number by the Froude number.

Two methods for performing these tests were considered; drop tests and aircraft tests. The disadvantages of the drop testing were the necessity of using very small models because of the limited space and zero-g time in the drop tower, and a test requirement that the model liquids should be distributed similiarly to the Centaur fluid prior to performing the simulated maneuver. In the case of the orientation maneuver, the liquid should be at the bottom of the model, while for the re-orientation maneuver, the liquid should be in the zero-g steady state configuration prior to simulating the maneuver. It was thought that the necessity of using the very small models might obscure detailed liquid motion because of high damping in small models. Therefore, consideration was given to performing these tests in the aircraft where zero-g times would permit the use of larger models. Experience gained in prior aircraft testing had demonstrated the difficulty in controlling the test conditions, and it was not immediately apparent that the test objectives could be accomplished using the aircraft.

Therefore, prior to finalizing the design and fabricating test hardware, exploratory tests were conducted in both the laboratory and aircraft to obtain evidence of the most feasible method of performing these tests.

Two flights were accomplished on the C131B aircraft to obtain evidence that sufficient time was available to first attain an equilibrium configuration of the fluid and then perform the simulated maneuver. A simple test capsule with a 1/35th and 1/60th scale model was used. Results of these flights clearly demonstrated that the zero-g time was not sufficient to damp out liquid perturbations due to deviations in the aircraft trajectory in models of this size. However, the use of smaller models would eliminate any advantage to performing the tests on the aircraft.

At the same time the aircraft exploratory tests were being performed, drop tests and liquid-liquid dynamic tests were conducted to visually determine the effects of damping in very small models. The preliminary investigations were simple rotations of 1/140th, 1/35th and 1/10th scale models. These models were photographed at frame speeds matched to their size according to the scaling laws. A visual analysis of the films showed that liquid motion was similar in the different size models, and therefore, that the scaling laws could be extended down to small model sizes. Based on these test results and the unsuccessful results of the preliminary aircraft tests, it was decided to perform the orientation and re-orientation tests in the two second drop facility.

The model selected was a 1/90th scale lucite tank. The Centaur parameters were then scaled to this model size and the model trajectory calculated. The test assembly consisted of the model and associated hardware for simulating the trajectory. The maneuver was initiated and terminated with calibrated and timed air blasts acting on two offset paddles mounted on the model. The model moved unrestrained in a vertical plane, but was restrained to this plane by a linkage with very low friction and small mass. The proper impulses were obtained by adjusting the blasts and the amount of offset of the paddles. Details of the model trajectory and hardware are contained in Reference 6. The test model was filled to 30% of its volume with Freon TF (simulating the first Centaur coast period). Three different portions of the trajectory were photographed with a 400 frame/second Milliken camera.

(1) The start and first acceleration period which simulated firing of the Centaur 50 lb. ullage rockets and the attitude control rockets.

(2) The coast period which simulated the Centaur period of constant rotation rate.

(3) The deceleration period and second coast which simulated the same period in Centaur.

Time delays of 20, 100 and 300 milliseconds were used before the start of the trajectory sequence to simulate as nearly as possible the liquid distribution in Centaur prior to performing the orientation and re-orientation maneuvers. The liquid was initially at the bulkhead end of the model in one-g. During the 20-msec zero-g time delay the ullage had just started to form, thus simulating the orientation maneuver. With 300 msec, the ullage was essentially completely formed into the hemispherically lowest energy configuration. This simulated the liquid distribution prior to a re-orientation maneuver, after a zero-g coast period.

An analysis of the films showed that during the first acceleration period the liquid started to fall back from its concave shape into a roughly flat surface. The kinetic energy of the liquid caused a dome to form in the center near the end of the acceleration period. In the long-time delay tests enough kinetic energy was left in the dome to form an appreciable jet squirting into the center of the tank. A rounded ullage then started to form and was completed before the deceleration. During this period of constant rotation rate, the ullage was greatly displaced by the rotation of the tank. The liquid displacement was opposite to the rotation, with most of the liquid lying along one side of the tank just before the deceleration. The deceleration period caused the fuel to rotate as a whole up and down the walls and across the ends of the tank. This sloshing occurred because the liquid continued to rotate for a time after the tank rotation slowed down and because the linear deceleration of the tank caused a higher head pressure along the one wall (because of a higher column of liquid) than along the opposite one. The liquid moved in the direction in which the tank had been rotating. After crossing the bottom, it travelled up the side of the tank wall in a column. Some "feathering" was displayed along the front edge of this column nearest the center of the tank. However, there was still a discernible ullage with the liquid next to the wall. After the deceleration period the liquid motion continued to move up and around the front of the tank and then back toward the bulkhead. There was some formation of bubbles near the dome of the intermediate bulkhead due to the impingement of the liquid on the bulkhead. Although the fuel was in a somewhat confused condition, there still was a well defined ullage with the liquid adjacent to the container walls. Some damping became apparent during this coast period after deceleration.

It should be noted that due to test schedule limitations and an error made during testing that this series of tests was not as complete as originally planned. It was proposed to investigate the effects of the orientation and re-orientation maneuvers on the liquid hydrogen at the beginning of and after both the first and second Centaur coast periods. During the first Centaur coast the liquid percentage of the total tank volume is 30%, while during the second Centaur coast period, the liquid percentage of the total tank volume is only 10%. Only the 30% fill case was investigated due to test schedule limitations. Furthermore the results of an error during testing with the 30% fill case prevented an accurate simulation of the orientation and re-orientation maneuver for the first Centaur coast period. This error was not uncovered until testing was complete. The tests were performed with the hardware apparatus adjusted for a 10% fill trajectory and with the model tank 30% full of liquid. The trajectory used (10% fill) differed from the 30% fill trajectory in that the accelerations were stronger, the velocities higher and the linear distance longer. Timing and all angular characteristics would be the same for both trajectories. An analysis of the two trajectories, discussed in Reference 6, led to the conclusion that this error did not appreciably affect the observed test results, and therefore, the results can be considered a good representation of what will occur in Centaur. In summary the test results clearly demonstrated that the liquid would be disturbed but that flow in general would be in a circular motion along the longitudinal dimension of the tank with gas in the middle and liquid along the walls. Therefore, it is not anticipated that the Centaur orientation maneuvers will affect center vent operation.

TABLE I

Time for Pull-Through to Occur in Centaur for Scheduled Pre-Start Chilldown Periods (4 Vernier Rockets Firing)
Required chilldown times - 33 sec.

	1st	2nd(30% liq.by vol)	3rd(10% liq. by vol)
LO_2 Tank	> 1000 sec*	> 1000 sec*	680 sec.
LH_2 Tank	> 1000 sec*	250 sec	61 sec.(H_2O Air)

* Estimated chilldown time

TABLE II

Time for Pull-Through to Occur in Centaur for Reduced "G" Pre-Start Chilldown Periods (2 Vernier Rockets Firing)

	1st	2nd (30% liq. by vol)	3rd (10% liq. by vol)
LO_2 Tank	> 1000 sec*	> 1000 sec*	680 sec.
LH_2 Tank	> 1000 sec*	190 sec.	37 sec**

* Estimated chilldown time

** Because Centaur propellant conditions will be more severe than test conditions, a successful zero-chilldown is not anticipated.

TABLE III

Time for Pull-Through to Occur in Centaur for Zero-G Pre-Start Chilldown Periods

	1st	2nd (30% liq. by vol)	3rd (10% liq. by vol)
LO_2	> 192 sec*	192 sec.	54.9 sec**
LH_2	> 136 sec.	43.1 sec**	4.3 sec.

* Estimated chilldown time

** Because Centaur propellant conditions will be more severe than test conditions, a successful zero-g chilldown is not anticipated.

TABLE IV

Settling-Outflow Test Results Converted to Centaur Time

% Fill Upper/Lower	Pre-Start Sequence	No. of Rockets	Settling Starts	Liquid at Bulkhead	Start of Childown Flow	Start of* Clear Flow	Gas Pull-Through
27-0	Second	2	0 time	8.9 sec	17.3 sec	102.5 sec	
15-15	"	"	"	"	16.8	61	
15-15	"	"	"	"	9.5	61.5	
15-15	Second	4	0 time	6.4 sec	9.2 sec	34.6 sec	
15-15	"	"	"	"	22.0	34.6	
15-15	"	"	"	"	11.4	42.4	
15-15	"	"	"	"	11.4	47.4	
5-5	Third	4	0 time	4.7 sec	5.1	28.5 sec	
5-5	"	"	"	"	14.0	27.3	
5-5	"	"	"	"	6.9	36.4	
5-5	"	"	"	"	9.5	29.1	
3-1/4 - 3-1/4	Third	4	0 time	4.7 sec	5.3 sec	29.8 sec	
	"	"	"	"	17.6	30.7	48.3 sec
	"	"	"	"	8.8	30.1	38.5
	"	"	"	"	2.3	31.0	
3-1/4 - 3-1/4	"	"	"	"	12.6	27.0	42.0

* Clear flow was arbitrarily selected as that condition which had 1% - 2% vapor by volume.

TABLE V

Influence of Gas Entrapment and Sloshing Upon Maximum Allowable Liquid Hydrogen Chilldown Outflow Times**

No. of Rockets	Third Pre-Start
4	63.1 sec* 10% liquid
	56.6 sec " "
	60.9 sec " "
	56.3 sec " "
	33.8 sec* 6.5% liquid
	31.8 sec " "
	30.1 sec " "
	24.2 sec " "

* No sloshing or entrapment during outflow

** Sufficient data was not obtained to present second pre-start results.

EQUIVALENT BUBBLE DIAMETER
VERSUS
MAXIMUM BUBBLE VELOCITY IN LIQUID HYDROGEN

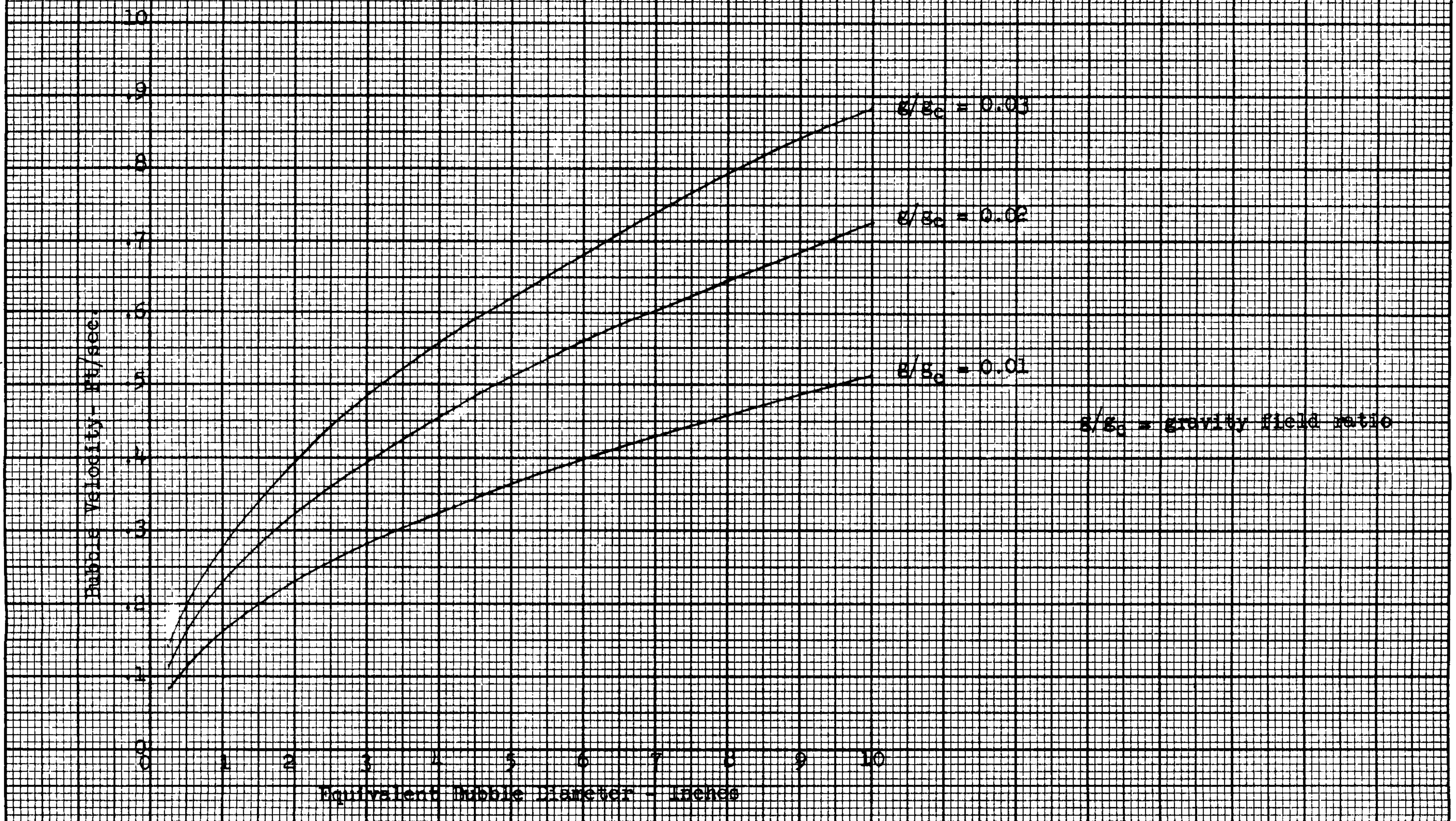


FIGURE 5

IV. VENTING TESTS

During extended Centaur coast periods, heat transferred into the fuel tank will raise the vapor pressure and necessitate the use of a vent device to relieve tank pressure. When the program was initiated, it was thought that conventional vent devices might not be adequate in a zero-g environment. If due to mechanical or thermal effects the liquid and gas during zero-g were randomly dispersed throughout the tank, a conventional vent device might vent liquid with the gas, causing propellant loss and subsequent reduction in vehicle performance. Therefore, as part of the zero-g test program, two methods of venting the Centaur fuel tank were investigated; a dynamic separator and a static device with no moving parts.

A. Dynamic Separator

Results of early testing on the C131B aircraft in 1959 indicated that a rotating device might solve the venting problem. A centrifugal separator device was subsequently designed and tested at Astronautics. A schematic drawing of the General Dynamics/Astronautics separator is shown in Figure 6. This vent device consists of two identical units, each containing a separator disc, control valve, turbine and heat exchanger. The two discs counter rotate to balance out their torque and prevent the vehicle from rolling during the zero-g period of the trajectory. Each disc consists of a circular flat plate with radially ducted holes, equally spaced, connected to a central hollow shaft. When the disc is rotating it will vortex the liquid hydrogen drawing the gas ullage bubble to it, thus allowing gas to vent through the holes.

Centrifugal forces prevent liquid from being vented.

Each separator disc is connected directly to a velocity compounded impulse turbine. When the tank pressure reaches a pre-determined value, a control valve opens allowing gas to flow to the turbine, starting it to rotate. Since the turbine is connected directly to the separator disc, the disc starts spinning clearing the holes of liquid hydrogen and drawing the gas ullage to it. Due to the differential pressure between the tank and turbine housing (vented to free space), the gas is cooled by its expansion in the turbine. To take advantage of this cooling process, the gas is then passed through heat exchangers before being vented overboard. This heat exchange process cools the liquid and gas in the tank, lowering pressure and subsequently the quantity of hydrogen vented.

As part of the test program, an 18 inch diameter scale model Centaur tank and two scale model separator rotors were built for testing in a zero-g environment. The test fluid was liquid nitrogen. The objective of this phase of the aircraft test program was to photograph the effects of the operation of the rotor on the liquid circulation and to determine if the separator will clear its "breathing hole" and vent just gas when submerged in liquid.

Early test flights in July and August of 1961 clearly demonstrated that because of the limitations of the test hardware and means of testing the test objectives could not be met. Excessive liquid motion prior to capsule release into zero-g prevented studying in detail liquid circulation patterns in the tank due to the rotating disc. This excessive liquid motion was caused by low order disturbances which occur prior to release into zero-g. The size of the test capsule and limited zero-g time available on board the aircraft

B. Static Vent Device

Knowledge gained as a result of liquid behavior studies made it possible to consider a center vent tube as a means of venting vapor only from the Centaur liquid hydrogen tank during coast periods. The vent tube represents the most mechanically reliable, due to simplicity, and the lightest vent system presently conceived.

The development of the liquid-liquid models clearly demonstrated that, for equilibrium conditions, liquid hydrogen will wet only a small portion of a tube inserted into the ullage region of liquid and gaseous hydrogen in a zero-g environment. A mathematical treatment of the shape of the liquid-gas interface around a center vent tube is presented in Reference 7 , and confirmed analytically the visual results. The observation made the feasibility of a vent tube more attractive because liquid losses due to flow along the tube would be essentially zero. Since liquid will not flow along the tube, the only way possible for liquid to be vented overboard is if forces act on the liquid to cause flow toward the tube inlet. The vehicle orientation maneuvers, and/or the venting process, could displace liquid toward the vent tube. The results of the orientation tests, Section III-C, showed that the maneuver would cause considerable liquid rotation but probably not cause liquid flow in the vicinity of a tube inlet located near the tank center. Liquid disturbances created by the venting process are discussed here and described in detail in Reference 8.

Boiling will be initiated during the venting process because of tank pressure reduction below liquid-vapor pressure. It is not definitely known how boiling will be distributed throughout the tank or which type of boiling will dominate. The extreme conditions would be for boiling to occur at the liquid-gas interface or at the tank walls. If boiling (evaporation) does occur at the liquid-gas interface, the liquid distribution will not be disturbed and vapor only will be vented. However, if boiling takes place at the walls, the ullage is initially reduced because vapor is vented without being replaced. Eventually the bubbles generated at the walls will coalesce with the ullage and further ullage reduction will cease. This condition can be regarded as the equilibrium ullage volume because the vapor vent flow rate is equal to the rate of vapor bubble coalescence with the ullage.

Hydrogen boiling during the venting sequence could not be simulated with model tests because of its complex nature. The only reasonable approach therefore was to select a venting model which would simplify the fluid behavior and would be conservative. The venting model selected assumed the following:

(1) No surface evaporation or boiling within the liquid.

(2) Boiling occurs at the intermediate bulkhead with the boiling rate equal to the vent flow rate.

(3) Vapor bubbles coalesce immediately upon contact.

(4) No liquid motion except that created by boiling.

This model was simplified because only wall boiling was considered. Earlier zero-g tests with liquid-hydrogen had shown that vapor bubbles coalesced immediately upon contact. This behavior was characteristic of the vapor of pure liquids such as liquid hydrogen. The model was conservative because surface boiling and bulk liquid boiling were not permitted. Each would cause the vapor bubbles to reach the ullage more rapidly than would peripheral joint boiling which permits bubbles to be generated at a maximum distance from the ullage. In addition, no liquid motion should increase the time required for bubbles to reach the ullage.

Based on this venting model, a theory describing the fluid behavior was postulated and venting tests were performed to verify this theory. The essence of the postulated theory was as follows. Vapor originating at the tank walls, during a venting sequence, while in a zero-g environment, can only be transported to the ullage by the mechanism of coalescence with other vapor bubbles. As a result of coalescence, bubbles will grow until contact is made with the ullage, at which time the bubbles will become part of the ullage. It seemed reasonable to assume therefore, for a given tank geometry and heating distribution, that a maximum vapor bubble volume would exist beyond which additional vapor generation would cause individual bubbles to merge and grow, such that coalescence with the ullage volume would occur at the same volume rate as vapor being vented from the ullage. The ullage volume that existed simultaneously with the maximum vapor bubble volume was the equilibrium ullage volume. Obviously, this equilibrium ullage volume was the minimum ullage volume that should exist in the tank during an extended vent sequence. The ullage volume was defined as that single volume of vapor which encompassed the vent tube inlet. The vapor bubble volume was the sum total of all the individual bubbles that are in the liquid. The time scale equation derived from the postulated fluid behavior was as follows:

$$\frac{t_c^*}{t_m^*} = \frac{\dot{V}_m}{V_m} \div \frac{\dot{V}_c}{V_c}$$

where

t^* = time to reach equilibrium ullage condition in hr.

V = total tank volume-ft^3

$\dot{V}$ = volumetric vent flow rate-ft^3/hr.

Subscripts c and m refer to Centaur and model. Model tests provided a value for t_m^* and $\left(\frac{\dot{V}_m}{V_m}\right)$. Because $\left(\frac{\dot{V}_c}{V_c}\right)$ is known for the Centaur vehicle, t_c^* could be determined from the equation.

Both liquid-liquid ground tests and zero-g 2-second drop tests were performed. The purpose of the liquid-liquid tests was to verify the time scaling equation. The drop tests were primarily for purposes of comparing fluid behavior in a zero-g condition with ground tests to demonstrate the validity of the ground test vent sequence. The secondary purpose was to conduct tests under more severe conditions than those expected in flight.

To obtain useful data from the liquid-liquid model tests, a method had to be found for making the liquid behave in a manner similar to that postulated for the ideal model. The liquid-liquid model simulation of the Centaur vent cycle was performed with 1/140th, 1/35th and 1/10th scale model fuel tanks. The simulated liquid hydrogen was a Freon-Stoddard solvent mixture and simulated gaseous hydrogen, distilled water. The simulated gas bubbles were formed by introducing water through orifices located as near the peripheral joint of the bulkhead as possible. A vent tube was inserted in the ullage for venting simulated gaseous hydrogen. To simulate the observed immediate coalescence of hydrogen bubbles, the tests were conducted in an electric field. The correct field strength was determined by visually comparing liquid coalescence to observed gaseous hydrogen bubble coalescence.

Water droplets were injected at various flow rates up to 10 tank volumes per hour into liquid-liquid models containing 30% "fuel" simulating venting during the parking orbit. The number of orifices was varied in each model. Data was taken with 1, 2 and 4 orifices on the 1/140th model, 2, 4 and 8 orifices on the 1/35th model and 2, 8 and 20 orifices on the 1/10th model. The range of venting rates maintained during tests was between 0.1 and 10 model tank volumes per hour. The expected Centaur liquid hydrogen tank vent rate is approximately 0.8 tank volumes per hour of vapor. A detailed description of the liquid-liquid model testing is contained in Reference 9.

An average curve of the data for the three models is shown in Figure 7. The vertical lines in the curves represent the data variation obtained from the tests, which was less for the larger models than the small model. The scatter was about ±30% for the large model, ±40% for the 1/35th model and ±65% for the small model. However, the slopes obtained from the 1/10th and 1/35th scale model tests were in fair agreement with each other. It can be seen from Figure 7 that the 1/35th scale model test results will predict a greater time period to attain equilibrium for any given vent rate. Therefore, using these extrapolated 1/35th scale test results it was found that about 110 seconds of continuous venting at 0.8 tank volumes per hour will be required to attain an equilibrium ullage volume in the Centaur during the parking orbit. This is equivalent to an ullage volume decrease of about 30 cubic feet.

The scatter in the data could be due to the error in visually determining when equilibrium had been established. It was difficult to achieve uniform flow through the orifices, and consequently, those bubbles which originated from a high flow rate orifice, coalesced with the ullage before time equilibrium could be obtained. Furthermore, the time required for bubbles to coalesce with the ullage, at a given total vent rate, varied depending upon the number of orifices in operation during the test. No relation was established regarding equilibrium times between the performance of one set of orifices with another set in the same model size, or with the same set of orifices in a different model size.

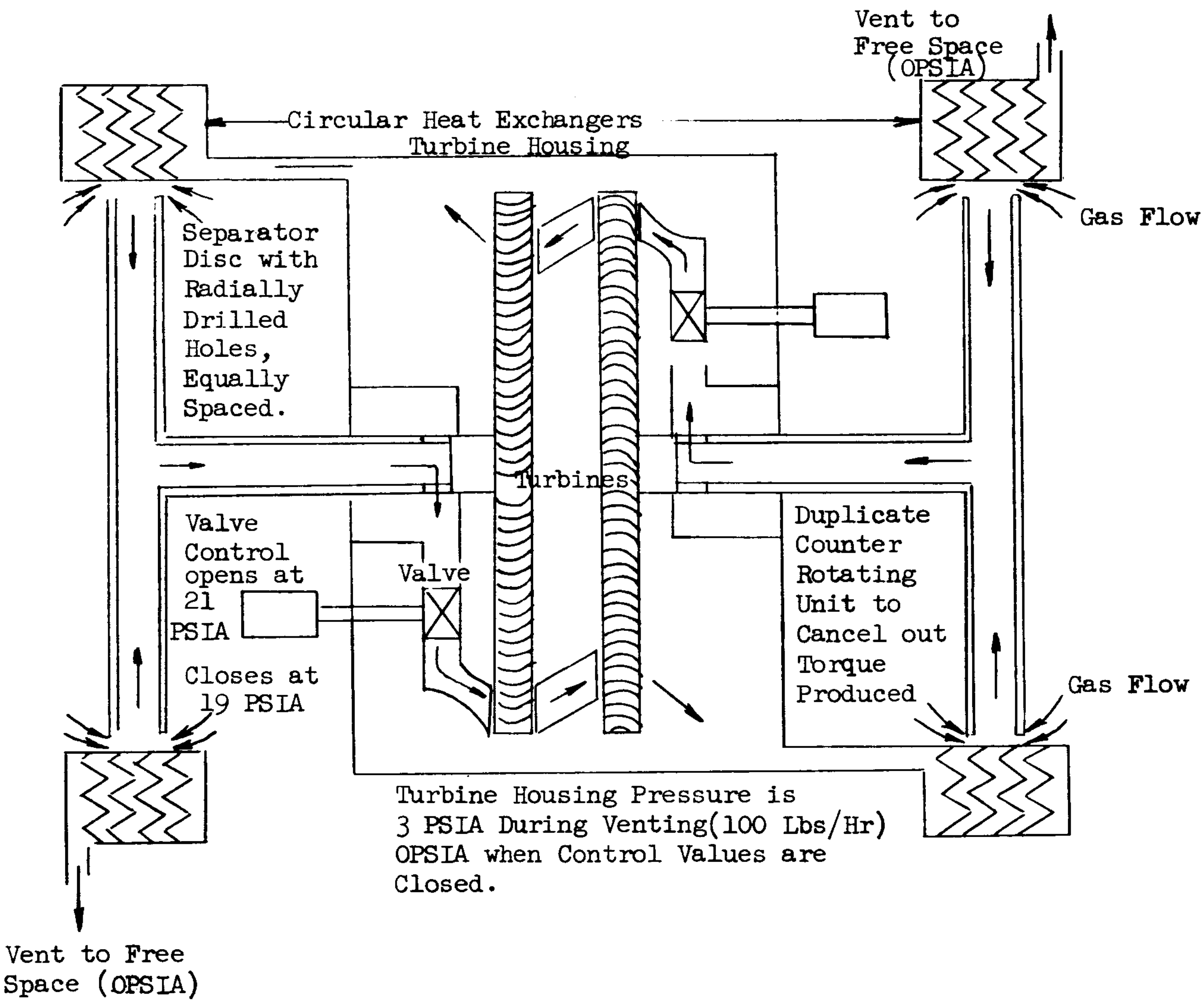
The test parameters during the drop tests were liquid fill and vent rates. A vent line with orifice and solenoid valve was connected to a 1/140th plexiglas model fuel tank. The test fluid was Freon 14 which was at its saturation temperature prior to the venting sequence. All boiling was initiated at the peripheral joint geometry during the vent sequence. The liquid fill was varied between 15% and 70% of tank volume, for venting rates between 1700 and 10,000 tank volumes per hour.

The drop tests yielded some general results, which revealed important information with respect to the Centaur vent tube. At the lower fill levels an equilibrium ullage was always attained. At the high fill levels (40% and greater) liquid was vented in the majority of cases of high vent rate (10,000 volumes per hour) and in about 50% of the cases of low vent rate (1800 and 4000 volumes per hour) tests. It should be noted that the short zero-g drop time and high model vent rates represent venting conditions more severe than are expected in Centaur. Because of the limited drop time available, even the short period required for bubble coalescence to occur was an appreciable portion of the total drop time. Thus, coalescence did not occur immediately as had been predicted. The result was that the equilibrium ullage volumes, as observed from drop tests, were smaller than predicted by the liquid-liquid model tests.

The simplified ground and drop tests have demonstrated that the vent tube has excellent potential as a venting device for Centaur. During the parking orbit less than 350 cubic feet of vapor will be vented during the first coast period. The initial ullage volume is 870 cubic feet, and therefore, there will be no opportunity for the liquid to approach the vent tube even if vapor coalescence did not occur. The drop tests results showed that during the second coast period the original ullage will experience only a small reduction before coalescence with bubbles, created at the wall, prevent further volume reduction. Again, there will be no opportunity for liquid to approach the vent tube inlet.

The center vent was further tested on an Aerobee shot in July 1962. The test results are not available at the present time. The purpose of the test was to determine if vapor only will be vented from the sphere while in a zero-g environment and if the vapor bubbles will coalesce and form a single central ullage following the vent cycle. Two venting cycles were accomplished during the flight and will be compared to determine any differences in liquid distribution. Motion picture coverage of the test was obtained and should show how rapidly the vapor bubbles, generated when the container pressure was reduced below saturation during the first vent cycle, will coalesce and form a single vapor bubble.

SCHEMATIC DRAWING OF THE CENTAUR ZERO-G LIQUID/GAS SEPARATOR



Nominal Operating Speed of the Separator Disc is 4000 RPM: This Speed Climbs to 8850 RPM when Surrounded by 100 Percent Quality Vapor.

FIGURE 6

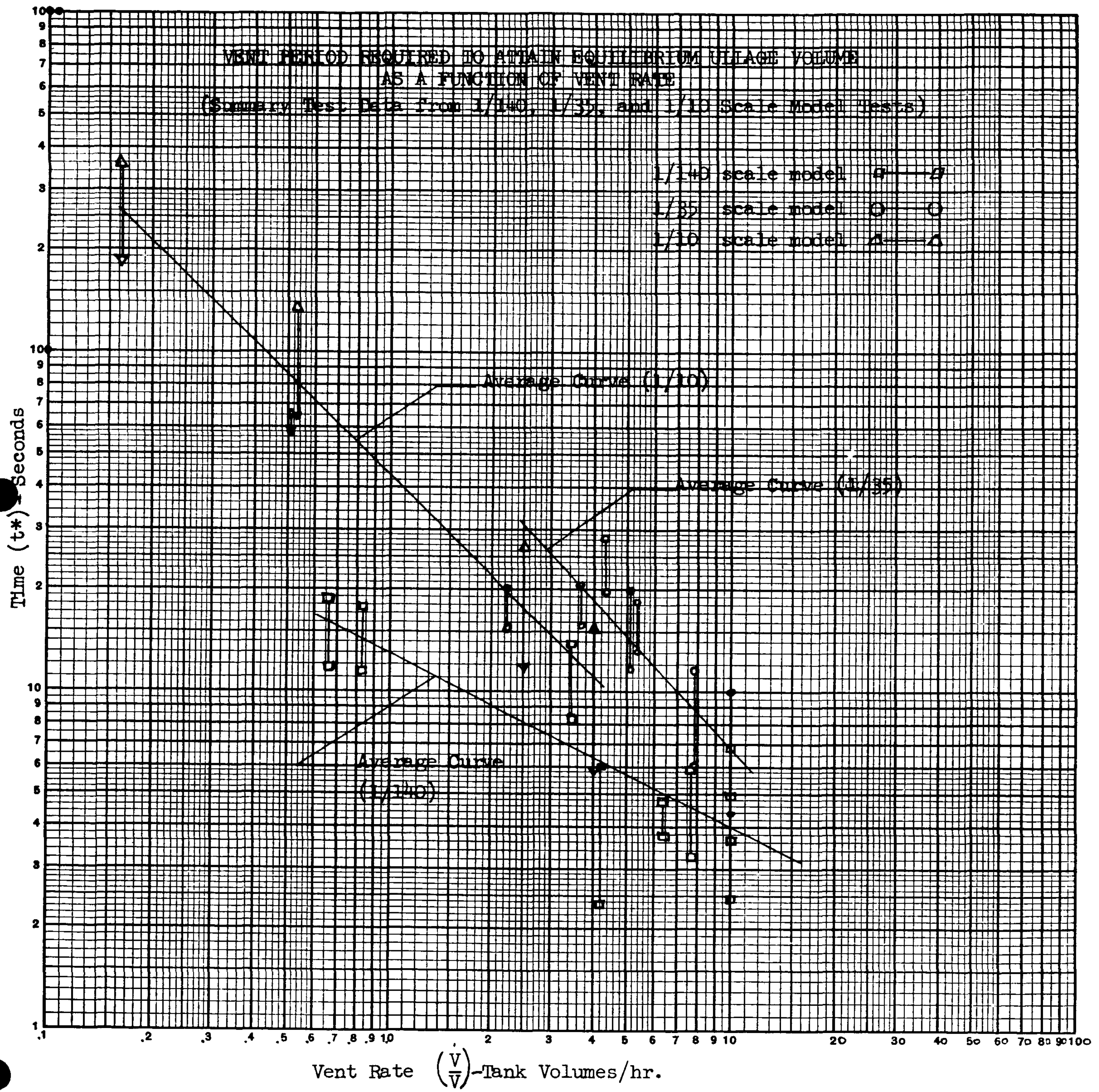

VENT PERIOD REQUIRED TO ATTAIN EQUILIBRIUM ULLAGE VOLUME
AS A FUNCTION OF VENT RATE
(Summary Test Data from 1/140, 1/35, and 1/10 Scale Model Tests)
1/140 scale model
1/35 scale model
1/10 scale model
Average Curve (1/10)
Average Curve (1/35)
Average Curve
(1/140)
Time (t*) - Seconds
Vent Rate $\left(\frac{\dot{V}}{V}\right)$-Tank Volumes/hr.

FIGURE 7

V. HEAT TRANSFER TESTS

The purpose of the heat transfer tests was to obtain evidence of boiling liquid hydrogen under heating conditions simulating those of an actual Centaur flight. The degree of understanding of heat transfer to and from fluids under zero-g is directly related to the accuracy in the prediction of propellant boil-off and the extent of optimization which can be reached in the design of a number of Centaur hardware items. The heat transfer areas investigated were as follows:

A. Liquid in Contact With the Centaur Fuel Tank Wall (Wall Boiling Tests).

B. Sudden Boiling When the Liquid Comes in Contact With a Warm Unwetted Surface (Warm Plate Impingement Test).

C. Liquid in Contact With the Peripheral Joint of the Intermediate Bulkhead.

A. Liquid in Contact With the Centaur Fuel Tank Walls

The primary objective of the wall boiling tests was to study the action of boiling on the face of a heated surface under zero-g conditions, i.e., to study the formation of the vapor and the coalescence or dispersion of the resultant bubbles and vapor. It was hoped that this visual study would show whether a stable gas film might form over the Centaur cylindrical tank surfaces during coast periods for a maximum expected heat input of 25 Btu/hr-ft^2. The propellant boil-off is directly related to the heat transfer between the tank surfaces and the liquid. Secondary test objectives included the following:

(1) Determination of the heat flux versus temperature difference between heated surface and liquid hydrogen in a zero-g environment.

(2) Determination of the threshold of the transition to film boiling.

(3) Determination of the minimum temperature difference required to initiate boiling in a zero-g environment.

Prior to zero-g testing on the airplane, laboratory tests were performed to develop the test hardware and to establish preliminary boiling heat transfer data in both a one-g and zero-g environment. The test assembly consisted of a glass dewar, a heater submerged in liquid hydrogen and instrumentation. A steady state technique was used to obtain the boiling heat transfer data. The problems connected with the measurement of very small temperature changes within a few seconds at liquid hydrogen temperatures led to the selection of a lead metal film deposited on an insulating substrate. Temperature differences in the order of .18°F could be detected and recorded at liquid hydrogen temperatures for a resistance between 5 and 10 ohms. The heated specimen was submerged in liquid hydrogen contained in a 4-liter glass dewar. The voltage across the specimen, the voltage drop across a known resistor (and, thus, the specimen current), as well as the voltage unbalance of the bridge were measured and recorded on a Sanborn and/or Midwestern recorder. The unbalance was due to the increase in specimen resistance which resulted from, and was used to measure, the temperature rise of the specimen. Additional instrumentation included for the aircraft tests was a high speed Miliken camera to obtain visual evidence of boiling at the heated surface. Details of the experimental apparatus are contained in Reference 10.

Test procedures for the drop tests and aircraft tests were similar. The lights, camera and recorders were actuated prior to release into the zero-g condition. The heated specimen was energized at release. To obtain satisfactory results from the photographic study, the aircraft tests procedures had to be revised slightly after the initial flights. Photographic observation of boiling at the heated surface was completely obscured by bubbles when the liquid hydrogen was at saturation temperature. To suppress boiling so that good evidence of boiling could be obtained, the capsule vent was closed as the aircraft trajectory approached the zero-g condition. However, because the effect of pressure and subcooling of the liquid on heat transfer data was not well known, all test conditions were performed at both an open and closed vent condition.

Under the test conditions outlined above, the lowest heat flux at which nucleate boiling was observed was 250 Btu/hr-ft^2 for a temperature rise of 2.3°F. It is felt that it was not possible to observe boiling at lower heat fluxes, comparable to the Centaur maximum heat flux of 25 Btu/hr-ft^2, due to a combination of the surface characteristics of the test specimen and the limited useable zero-g available on board the aircraft. It is known that the characteristics of the heated surface play an important role in the boiling phenomenon. For example, less superheating is required to initiate boiling on a rough surface with many effective nucleation points than on a smooth surface. The lead specimen used throughout these tests had a fairly smooth surface. Therefore, it is concluded that boiling would have been observed at lower heat fluxes with this specimen if a longer zero-g test time had been available or if the lead surface had been a rough finish with an increased number of effective nucleation points. Visual observation of boiling for a range of heat fluxes between 250 Btu/hr-ft^2 and 1000 Btu/hr-ft^2 showed that the bubbles formed at the heated surface rapidly coalesced and, in every case, the surface tension forces were sufficient to rewet the surface behind the bubble. At the higher heat fluxes, the aircraft capsule geometry limited a detailed study of the bubble growth for extended periods of zero-g. Baffles were located above and below the test specimen to keep the ullage away from the heated surface during the zero-g condition. A preliminary analysis of the recorded data indicated that the threshold of film boiling had been reached shortly after release into a zero-g environment. However, correlation of this data with the film data showed that the bubbles generated at the heated surface coalesced, forming a larger bubble, until the baffle located approximately 1-5/8 inches above the specimen restricted the bubble and forced it against the test specimen. To help eliminate this condition so that boiling at the higher heat fluxes could be observed for longer periods of zero-g, the heater was inverted and the bottom baffle removed which allowed approximately 4 inches for the bubble to grow below the test specimen. Results showed that the test specimen started to dry out for heat fluxes in the range of 7000 Btu/hr-ft^2. Because of the camera position, it was not possible to determine whether or not the bubble was restricted in any way. The drop capsule did not necessitate the use of baffles and recorded data of heat flux versus temperature rise indicated that the transition to film boiling occurred between 12,000 Btu/hr-ft^2 and 18,000 Btu/hr-ft^2 with a corresponding temperature rise near 11°F. However, camera coverage was not available during these drop tests and therefore it is not known if the transition to film boiling occurred because of vapor bubble restriction.

The heat flux as a function of temperature rise between the test specimen and liquid hydrogen was determined from the resistance versus temperature relationships of the specimen. A best curve fit at one-g was statistically obtained from nearly 100 points of heat flux versus temperature rise, Figure 8, and used as a reference for comparison with zero-g data. A range of heat fluxes between 25 Btu/hr-ft^2 and 25,000 Btu/hr-ft^2 was considered. A heat flux of 250 Btu/hr-ft^2 was required to initiate boiling at a temperature rise of 2.7°F. A heat flux of 25,000 Btu/hr-ft^2 was required to initiate the transition to film boiling at a temperature rise near 11.5°F. Data of heat flux versus temperature rise at zero-g are shown in Figure 9 and includes both drop test and aircraft test data for liquid hydrogen at saturation temperature. The data obtained during tests with boiling suppressed were not included because, as mentioned previously, the effect of pressure and sub-cooling of the liquid on heat transfer data was not known.

A comparison of the two curves of Figures 8 and 9, given in Figure 10, shows that for the particular heater orientation used throughout these tests the zero-g and one-g boiling heat transfer data are approximately the same. At the present time no adequate explanation exists to fully explain this phenomenon. It appears that continual formation of vapor at the heated surface augments the convection process and provides the means for a better than expected heat transfer in zero-g. One possible explanation is that the heat transfer is primarily attributed to the process of nucleation and microconvection in the heated boundary layer close to the heated surface and that this process is only to a very small extent gravity dependent. Thus, the removal of bubbles plays only a secondary role. However, the state-of-the-art for zero-g boiling heat transfer data is such that further investigation is needed to fully explain this phenomenon.

Although it was considered beyond the scope of the program to perform more extensive experimental tests to fully interpret the data and to study the influence of other variables, one additional laboratory investigation was performed which did help to supplement the data already obtained. A test was conducted to determine the minimum temperature difference (between a heated wall and liquid hydrogen at its boiling point) required to initiate boiling (i.e. formation of bubbles) in zero-g. The test equipment consisted of an isolated cell of liquid hydrogen arranged so that the top plate of the cell could be heated and the formation of bubbles observed.

Heating the plate from the top eliminated convection currents and thus simulated a zero-g condition. The cell was immersed in a 25 liter dewar of liquid hydrogen. Details of this test are presented in Reference 11. Three different plates were used with different surface finishes. Boiling started for a temperature difference less than 0.2°F Δ t on a relatively rough surface, with several nucleation points, but a 6°F temperature difference was required for a plate with a very smooth finish, (1.25 micro inch RMS). As a result of this test, it is felt that the temperature of the Centaur tank walls will not be appreciably above the liquid hydrogen boiling point. The welds on the internal surfaces of the Centaur fuel tank will supply an almost infinite number of nucleation sources.

It is recognized that the results of this phase of the program are limited and that considerable care should be used in extrapolating the results to predict Centaur heat transfer phenomenon. However, it is felt that certain broad conclusions can be safely drawn from these tests and applied to Centaur, particularly when combined with the knowledge of the liquid gas equilibrium configuration in Centaur during coast periods and the Aerobee test results. During the parking orbit and transfer ellipse, large portions of the Centaur cylindrical tank walls will be wetted with only a molecular layer of liquid hydrogen. This is particularly notable during the transfer ellipse where the liquid percentage of the total tank volume is about 10%. For purposes of computing the heat input to the hydrogen tank, these sections of the tank surface can be considered dry surfaces. On those surfaces where the liquid thickness is greater, it is expected that boiling most likely will occur for a maximum heat input of 25 Btu/hr-ft^2. The fact that boiling could not be observed at this heat flux on board the aircraft is felt to be a limitation of the test hardware and the limited available zero-g time. Because the thermoconductivity of liquid hydrogen is so low, the liquid temperature adjacent to the cylindrical tank wall should increase until a sufficient temperature difference is attained to create boiling. The welds on the internal tank surface of the fuel tank will supply an almost infinite number of effective nucleation sources and boiling should occur for very little superheating. For an undetermined period of time, the bubbles formed at the heated surface will coalesce and the surface tension forces will be sufficient to rewet the surface behind the bubble. It cannot be predicted how long a period of time the wall will remain wetted under these conditions. Information on the transition from nucleate boiling to film boiling (wet wall to dry wall in Centaur) can not be predicted from the data obtained during testing. Film boiling was never observed unless the bubble was restricted. However, results of Aerobee tests, although not completely analyzed or understood at the present time, do indicate that after a definite period of zero-g the surface will start to dry out. During the initial stages of the zero-g portion of the Aerobee flight, the walls were completely wetted with liquid hydrogen. However, the thickness of the liquid layer was not uniform. After approximately 200 seconds of zero-g and for a range of heat fluxes between 160 Btu/hr-ft^2 and 270 Btu/hr-ft^2, drying began where the thickness of the liquid film was least. Thus, it appears that a wet or dry wall condition may be dependent upon both the zero-g time available and the thickness of the liquid layer. In summary, it is expected that large sections of the Centaur tank walls will be dry during the parking orbit and transfer ellipse. It is even possible that the entire cylindrical tank walls will be dry after the Centaur has been in a zero-g environment for an extended period of time. Data is not available at the present time for estimating this period of time.

B. Sudden Boiling When the Liquid Comes in Contact With a Warm Unwetted Surface.

It was considered possible that due to mechanical or thermal effects portions of the Centaur tank surfaces and bulkhead would not be wetted by liquid hydrogen during coast periods. Upon firing of the settling rockets, therefore, the liquid hydrogen would come in contact with relatively warm unwetted surfaces as the vehicle gains momentum. It was considered possible that vapor formation would be violently forcing liquid away from these surfaces and adding to the settling problem of liquid hydrogen. Therefore, the test objectives for this phase of the program were:

(1) To determine the manner in which vapor is formed when liquid hydrogen is brought into contact with a warm surface under zero-g.

(2) To determine the rate of heat transfer from the warm surface to the liquid hydrogen under zero-g conditions.

All tests were run in an equipment capsule which consisted basically of a 4 liter pyrex dewar containing the liquid hydrogen "percolator" and heated specimens, a motion picture camera, timing and illuminating lights, and a tubular framework to support the foregoing. Electrical power to the capsule was supplied by an external "trailing wire".

The liquid hydrogen was impinged against the heated specimens by means of the percolator located inside the dewar. A resistance heating element, inside the reservoir of the percolator, was energized and a relatively large hydrogen gas bubble formed. The expansion of this bubble forced liquid hydrogen out of the reservoir, up a connecting tube and against the plate specimen at velocities of 1/2 to 1 foot/second. The particular plate specimen under test was physically located 1 inch above the percolator tube normal to the stream of impinging liquid hydrogen.

Two types of warm plate specimens were used; stainless steel and copper. The stainless specimen was used to study vapor behavior while heat transfer coefficients were established with the copper plate. Details of the test assembly are presented in Reference 12. The temperature spectra of the plates was so chosen to cover all probable values of the Centaur vehicle in flight. Plate temperature of 100, 200 and 300°R were selected for liquid surface velocities of 1/2 to 1 foot/second.

Analysis and reduction of film and recorder data showed conclusively that the impingement of liquid hydrogen against a relatively warm steel surface, in the temperature range of 100°R to 300°R, results in no appreciable rejection or repulsion of the liquid. Therefore, no additional complications to the settling problem need be feared from the eventually of liquid hydrogen impinging against warm unwetted Centaur surfaces.

To calculate the film boiling heat transfer, the following assumptions were made:

(1) Since the copper plate was guarded, the only temperature gradient present was normal to the exposed surface.

(2) Since the thermal conductivity of copper was high and the plate was thin, the temperature gradient through the plate was assumed negligible.

The rate of heat loss per unit area (heat flux) is,

$$q = \frac{MC_p}{A} \quad \frac{dT}{dt}$$

where:

q = heat flux

M = the mass of the plate

C_p = the specific heat of copper

A = the surface area

$\frac{dT}{dt}$ = the rate of change temperature with time (Sanborn recording)

Two trajectories were flown without the liquid being impinged upon the stainless steel plate. From this the heat flux to hydrogen gas was obtained. These values were subtracted from the heat loss from the back of the plate to the gas. The results are presented in Figure 11.

C. Liquid in Contact With the Peripheral Joint of the Intermediate Bulkhead

As part of the proposed zero-g aircraft test program, it was planned to determine the heat transfer from the liquid oxygen tank to the liquid hydrogen tank through the peripheral joint. It was thought that knowledge of the heat transfer in this area was important in order to more accurately estimate the liquid hydrogen boil-off and liquid oxygen tank pressure for all phases of flight. Calculations showed that conduction through the many layers of stainless steel skins in this area amounted to approximately one-half of the total bulkhead transfer, assuming the surfaces were wetted with liquid. However, if gas formed in this area thus forcing liquid hydrogen away from the peripheral joint, this would cause a decrease in the heat transfer from the liquid oxygen to the liquid hydrogen tank. To insure an optimum design for the vehicle, it was therefore felt necessary to be able to predict the heat transfer conditions at the peripheral joint.

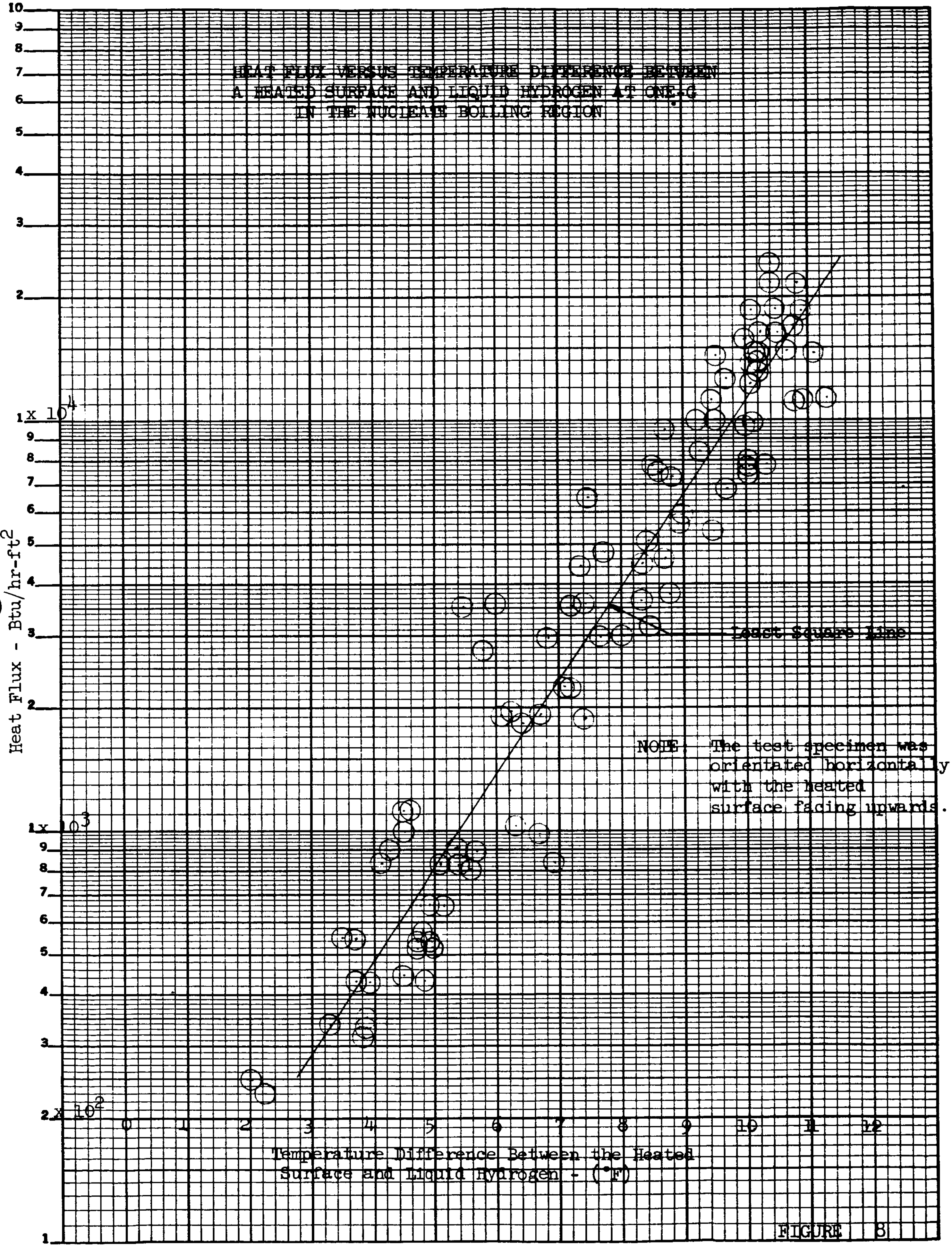
Initially, it was planned to perform the peripheral joint heat transfer tests on the aircraft. However, as the aircraft test program progressed and experience was gained, it became evident that it would be difficult if not impossible to accomplish the test on the aircraft. In the majority of maneuvers, the liquid was considerably disturbed prior to release into zero-g. Furthermore, the useable zero-g time available was not sufficient to observe the behavior of boiling in this region under equilibrium conditions. Because it appeared that the tests could not be accomplished on the aircraft, a laboratory exploratory type test was initiated in an effort to gain some knowledge of the heat transfer in this area. The specific objective of this investigation was to determine if the vertex of the Centaur peripheral joint would remain wetted under zero-g conditions. To accomplish the objective an effort was made to simulate a condition more severe than might be expected in a zero-g environment.

The Centaur peripheral joint is made of several thicknesses of steel welded together. The simulated joint used during the laboratory investigation was made of only two pieces, one for each side, but of the same total thickness. One side was .04 inches and the other .025 inches. The liquid oxygen end of the simulated joint was a .375-inch diameter tube through which a fluid could be passed to vary the temperature. One copper-constantan thermocouple was located at the vertex (T_B) of the joint and another at the tube (T_A) to measure the temperature. The original intent was to seal the ends of this simulated joint with polyurethane foam and submerge the joint horizontally in the hydrogen with the upper leaf slightly above the liquid surface. It was theorized that with the ends sealed the bubbles formed would have to move in a direction opposite to that of the liquid moving in to replace it. Because the apex is above the liquid level, the liquid would be pulled into it by the surface tension forces acting against gravity. It was reasoned that if the vertex stayed wetted under this condition, which is more severe than zero-g, then it would surely be wetted in the absence of gravity. However, three attempts to insulate and seal the joint with polyurethane foam failed. The simulated joint was then sealed in a welded steel box and the unit installed in a pyrex dewar so that boiling in the joint could be observed. The pressure inside the box was reduced to below one micron when surrounded with liquid hydrogen due to the condensation and freezing of the air at that temperature. With this testing apparatus, the ends of the joint were not closed to prevent the edgewise flow of hydrogen nor was the upper surface of the joint held above the liquid surface. Therefore, the desired simulated condition more severe than zero-g was not obtained. However, tests were conducted with the apparatus discussed above to measure the temperature of the vertex with the simulated joint immersed in liquid hydrogen.

The heat flux through the peripheral joint was predicted by assuming that the heat flowed from the oxygen side through the skins to the vertex of the joint and then dissipated to the hydrogen with each side acting as a fin. The heat transfer coefficient was taken from Reference 40. The coefficient was assumed constant over the fin at the value which would exist for the temperature difference at the vertex. With increasing flux, the temperature of the vertex would finally reach that for peak nucleate boiling. At any flux higher than this, it was assumed that a region of film boiling existed from the vertex to a point where the fin temperature would have dropped to that of peak nucleate boiling.

The measured temperature at the vertex (T_B) was higher than predicted when the simulated joint was immersed in liquid hydrogen as shown in Figure 12. Even though the measured temperature was greater than that which should exist for nucleate boiling, according to the data obtained by many investigators, the vertex appeared to be wetted by the hydrogen all the time. It was expected that the temperature would be slightly lower than predicted due to the additional fin surface at the edges of the simulated joint. Due to this additional surface at the edges, no bubbles were formed in the vertex at the edge. The liquid could therefore circulate toward the vertex at the edge and then toward the center to replace that which was vaporized there. The desired counter flow of liquid and bubbles did not occur. Thus, the simulation of a condition more severe than zero-g was not obtained. It is felt that the vertex indicated temperature was slightly higher than predicted due to conduction down the thermocouple. The heat transfer through the joint as a function of the oxygen side temperature was measured to be approximately 90% of the predicted rate. The heat transfer rate is less sensitive than the temperature distribution to slight errors in temperature measurement. Although the visual observations were in disagreement with the measured temperatures,it is concluded that the temperature measurements were in error and that the vertex was in fact wetted.

Because a condition more severe than what might be expected in zero-g could not be simulated, these test results can not be used to predict peripheral joint heat transfer in Centaur. The pressure limits of the liquid oxygen tank were designed to assure vehicle operation under eithercondition; that is, a wet or dry joint. Optimization of the liquid oxygen tank pressure limits was not possible based on these tests.


HEAT FLUX VERSUS TEMPERATURE DIFFERENCE BETWEEN
A HEATED SURFACE AND LIQUID HYDROGEN AT ONE-G
IN THE NUCLEATE BOILING REGION
Heat Flux - Btu/hr-ft^2
1 x 10^4
1 x 10^3
2 x 10^2
Least Square Line
NOTE: The test specimen was orientated horizontally with the heated surface facing upwards.
0
1
2
3
4
5
6
7
8
9
10
11
12
Temperature Difference Between the Heated Surface and Liquid Hydrogen - (°F)
FIGURE 8

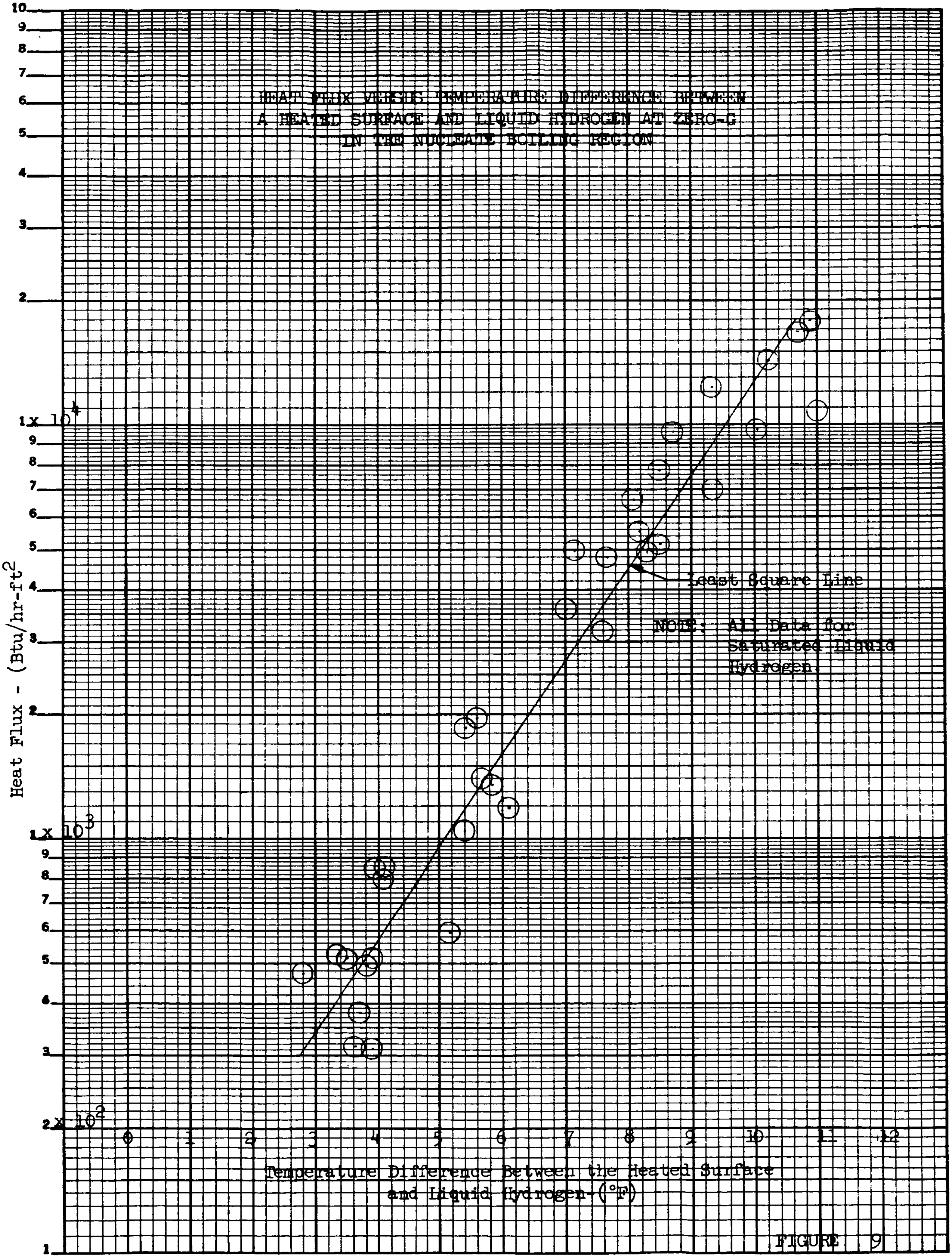
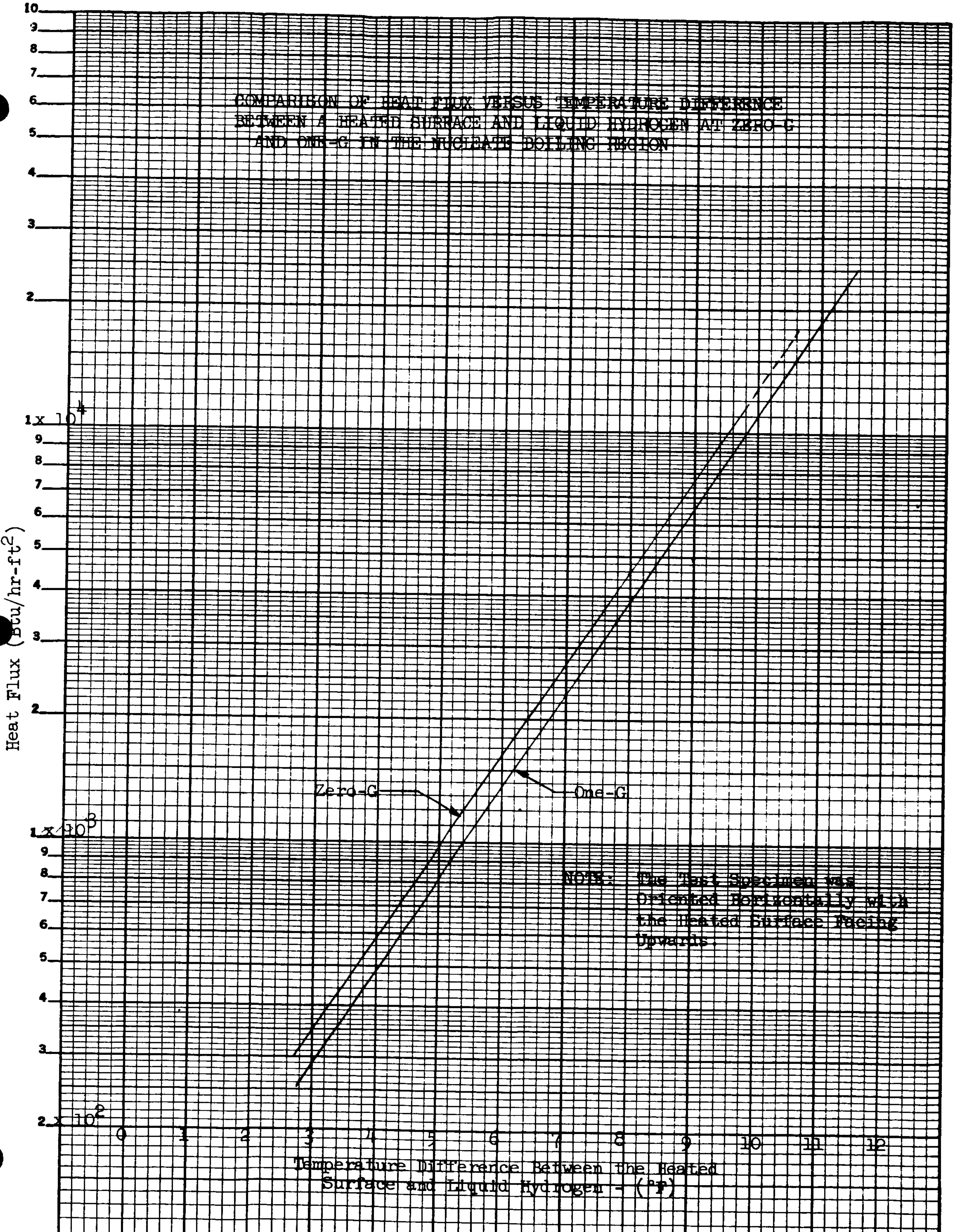

HEAT FLUX VERSUS TEMPERATURE DIFFERENCE BETWEEN
A HEATED SURFACE AND LIQUID HYDROGEN AT ZERO-G
IN THE NUCLEATE BOILING REGION
Least Square Line
NOTE: All Data for Saturated Liquid Hydrogen.
Heat Flux - (Btu/hr-ft^2)
Temperature Difference Between the Heated Surface and Liquid Hydrogen-(°F)
1 x 10^4
1 x 10^3
2 x 10^2
0
1
2
3
4
5
6
7
8
9
10
11
12

FIGURE 9



COMPARISON OF HEAT FLUX VERSUS TEMPERATURE DIFFERENCE
BETWEEN A HEATED SURFACE AND LIQUID HYDROGEN AT ZERO-G
AND ONE-G IN THE NUCLEATE BOILING REGION
Heat Flux (Btu/hr-ft^2)
1 x 10^4
1 x 10^3
2 x 10^2
Zero-G
One-G
NOTE: The Test Specimen was Oriented Horizontally with the Heated Surface Facing Upwards.
0
1
2
3
4
5
6
7
8
9
10
11
12
Temperature Difference Between the Heated Surface and Liquid Hydrogen - (°F)

FIGURE 10

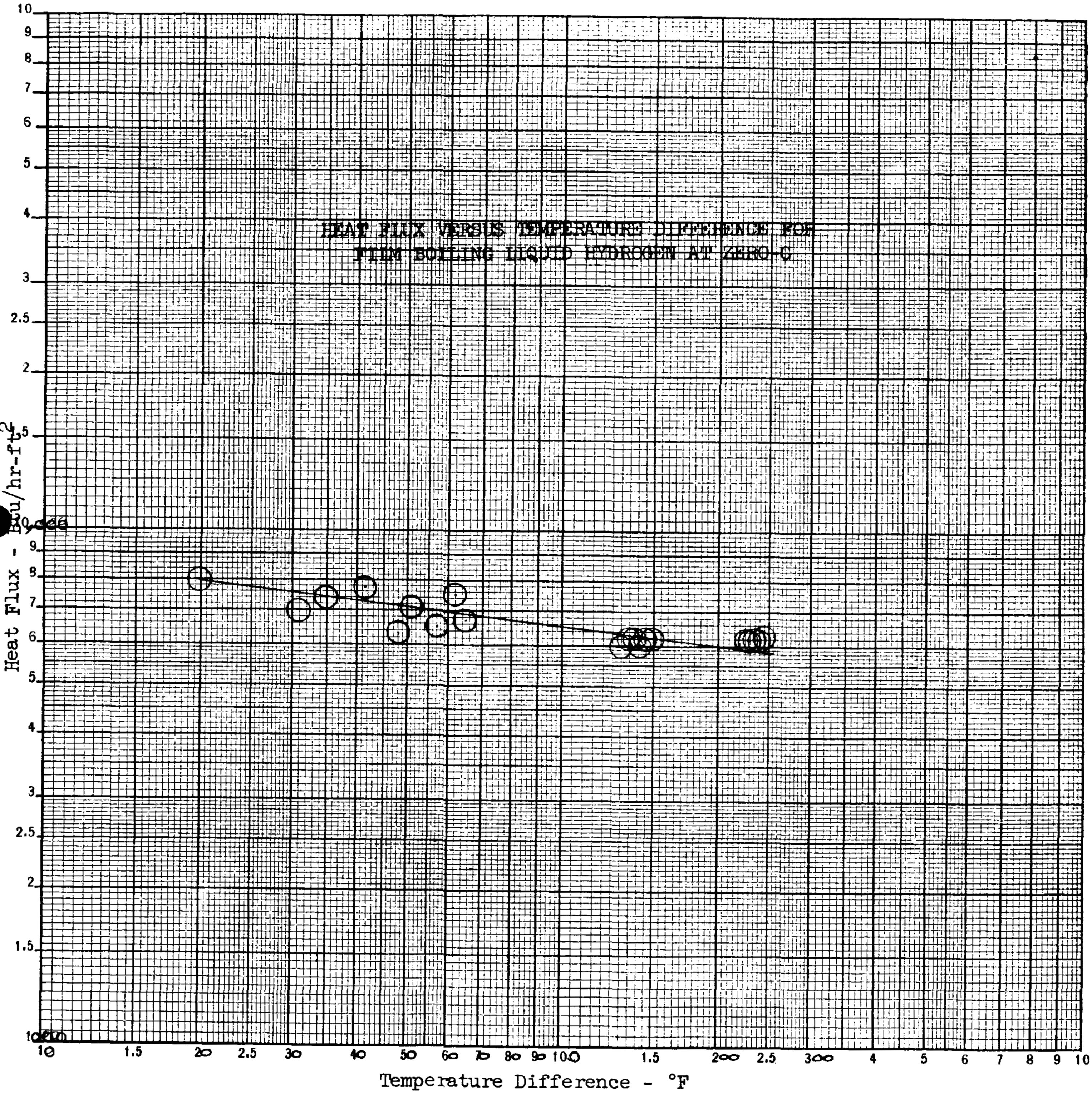
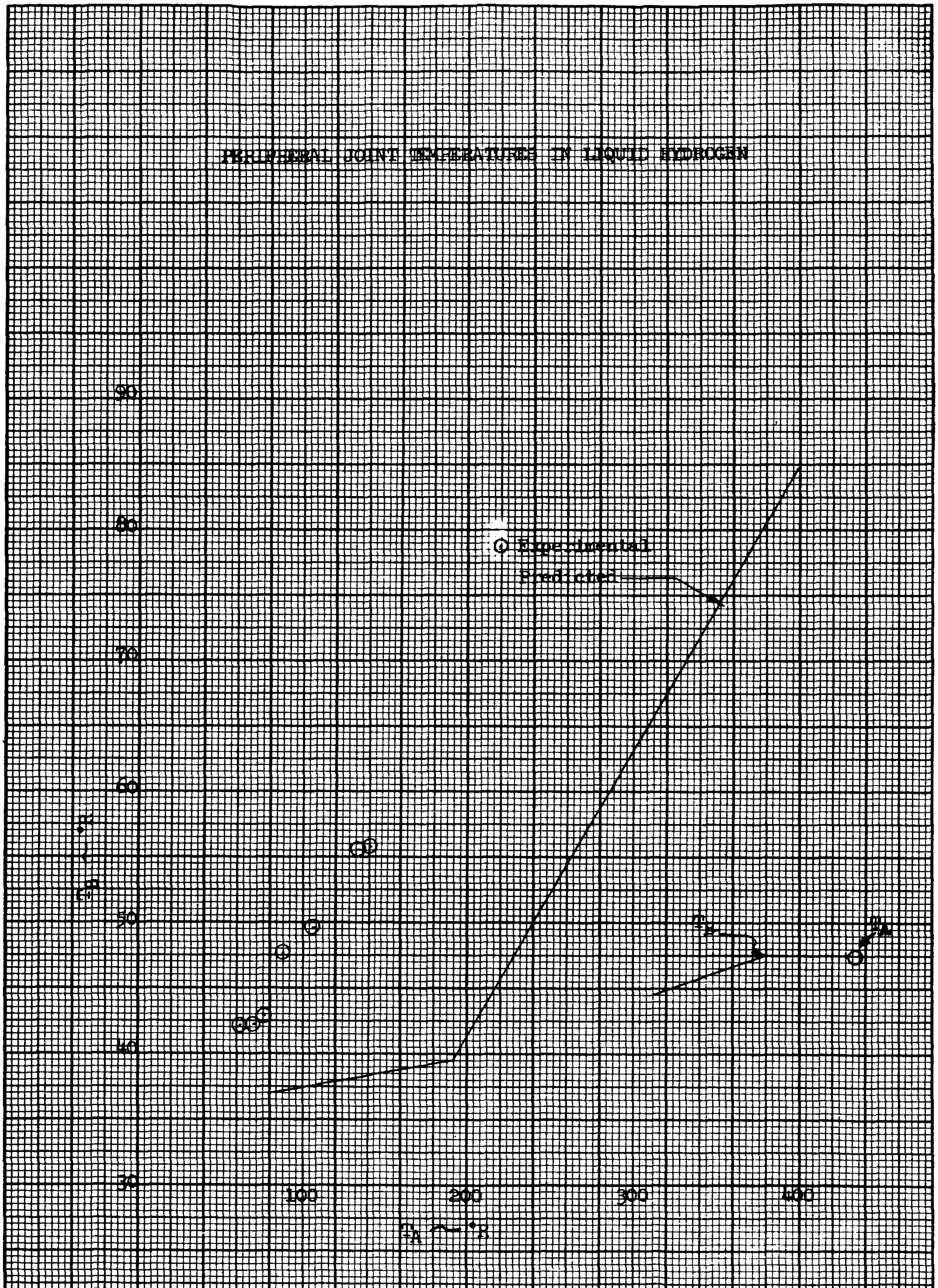

HEAT FLUX VERSUS TEMPERATURE DIFFERENCE FOR
FILM BOILING LIQUID HYDROGEN AT ZERO-G
Heat Flux - Btu/hr-ft^2
Temperature Difference - °F
10,000
1000
10
1.5
20
2.5
30
40
50
60
70
80
90
100
200
300

FIGURE 11


PERIPHERAL JOINT TEMPERATURES IN LIQUID HYDROGEN
Experimental
Predicted
T_B
T_A
90
80
70
60
50
40
30
$T_B \sim {}^\circ R$
100
200
300
400
$T_A \sim {}^\circ R$
FIGURE 12

VI. LIQUID VAPOR-SENSOR TESTS

A performance evaluation of liquid-vapor sensors in a zero-g environment at liquid hydrogen temperatures was performed as part of this test program. Initially it was thought that the performance of currently available liquid-vapor sensors might be adversely affected by the lack of normal gravity and the very low temperatures. A compromise of Centaur telemetered data could result from unsatisfactory performance of the liquid-vapor sensors mounted in the Centaur fuel tank.

A detailed description of the experimental tests performed to evaluate several liquid-vapor sensors in both a normal gravity and zero-g environment is contained in Reference 13. Four sensors of various types (capacitance, vibratory and hot wire) were selected for testing. The test objectives were as follows:

(1) Determine the reliability of the probes at liquid hydrogen temperatures.

(2) Determine the time response of each probe into and out of the liquid hydrogen.

(3) Determine if liquid hydrogen tended to adhere permanently to the capacitance probe and if the vibratory and hot wire probes tended to reject the liquid when completely submerged during the zero-gravity condition.

(4) Determine if the sensors and their support structures affected the liquid distribution in a zero-g environment.

(5) Select the instrumentation for installation on the Centaur vehicle.

Early in the test program objective 4 was considered particularly important because of the proposed method of installing the liquid-vapor sensors in the Centaur fuel tank. The sensors are mounted on a "Christmas Tree" like structure hanging within the tank. It was considered possible that the liquid hydrogen might "creep" along the branches of the "Christmas Tree" and the probes and wet the sensing element, thus causing the probe to indicate liquid when essentially in a gas environment.

The four liquid-vapor sensors selected for evaluation were a Minneapolis Honeywell capacitance probe, a Transonics and Acoustica vibratory probe and a General Dynamics/Electronics hot wire probe. The capacitance and vibratory probes were cycled in liquid hydrogen approximately 100 times to determine their response time. To obtain a preliminary indication of the probes performance in a zero-g environment, all probes were dropped 18 feet in an instrumented box which yielded approximately 1 second of zero-g time. The probes demonstrating the most satisfactory performance were then tested on the KC135 aircraft where useable zero-g times up to 15 seconds were obtained. An additional test on an Aerobee shot was performed with the probe selected for installation on Centaur.

A summary of the results of the one-g laboratory tests is contained in Table VI. Results of the preliminary laboratory zero-g tests eliminated the Minneapolis Honeywell and Transonics probes from consideration for installation on Centaur. If the probes were mounted in liquid prior to the zero-g condition, such that during the zero-g period they would be in a gas environment, they consistently indicated liquid. An analysis of the film results showed that the liquid clung to or was trapped in the probes sensing element. The results of drop tests with the Acoustica probe and General Dynamics/Electronics probe were inconclusive. When the probes were submerged in liquid hydrogen prior to the drop, such that during the zero-g condition they were in the ullage, a film analysis indicated that both the probes sensing elements and support structures remained wetted by the fluids. However, unlike the Minneapolis Honeywell probe and the Transonics probe, this condition did not always cause the Acoustica probe and General Dynamics/Electronics probe to indicate liquid when essentially in a gas environment. The drop test times were too limited to determine if the response of the latter two probes were dependent upon the amount of liquid wetting the sensing element, or whether the sensing element would repel small quantitites of liquid.

The Acoustica and General Dynamics/Electronics probes were then tested on board the KC135 aircraft where longer zero-g times could be obtained. The test results showed that the sensing element of the probes remained wetted with liquid hydrogen if sloshed with the liquid prior to entering the zero-g condition. For the General Dynamics/Electronics probe, if the sensing element was more than 1/3 covered with liquid hydrogen, the probe indicated liquid when essentially in a gas environment. In the case of the Acoustica probe, it was observed that a globule of liquid formed around the sensing element and that in a few instances this layer of liquid caused the probe to indicate liquid when essentially in a gas environment. However, it was difficult to determine the thickness of liquid which would cause this probe to read incorrectly because of the infrequent number of times this occurred. The best estimate of the liquid thicknesses which would cause the probe to indicate liquid when essentially in a gas environment was 1/4 inch. There was absolutely no indication that either probe would repel even these small quantities of liquid for the zero-g times available during the testing.

It was not possible to investigate the liquid creep phenomena in either drop or aircraft tests. Useable zero-g times available were not long enough for the liquid to reach a stablized configuration in the 4 liter test dewar used throughout these tests. Although difficulty was encountered in investigating this phenomena during these tests, experimental and theoretical information obtained from liquid behavior studies and liquid-liquid models did show that the liquid fillet around a protrusion into the central ullage would extend only a few diameters into the bubble, except for an absorbed microscopic layer. Therefore it was concluded that liquid creep would not be a problem.

Although the results of zero-g tests on board the aircraft indicated that the Acoustica probe might be less effected by liquid retained around the sensing element than the General Dynamics/Electronics probe, the latter probe was selected for installation on the first three Centaur vehicles. Weight and power requirements of the General Dynamics/Electronics probe were far more compatible with missile requirements. A sketch of the General Dynamics/Electronics probe is shown in Figure 13.

To obtain an indication of the performance of the General Dynamics/ Electronics probe in a zero-g environment for a longer period of time, two probes were mounted in the test sphere of an Aerobee missile. Approximately 3-1/2 minutes of zero-g were obtained during the flight prior to an electrical malfunction of both probes. The results were compatible with aircraft test results with this probe. The probe mounted in gas during one-g indicated liquid approximately 2 seconds after burnout due to liquid being sloshed against it. The probe mounted in liquid prior to the zero-g condition indicated liquid throughout the flight, thus substantiating aircraft test results that the liquid is retained around the sensing element of the probe.

The performance of the General Dynamics/Electronics probe in a zero-g environment is now well known and therefore data reduction of flights F-1, F-2, and F-3 should yield useful information.

TABLE VI

SUMMARY OF THE LIQUID-VAPOR SENSOR

LABORATORY TESTS

	Liquid-Vapor Sensor	Response Time Into LH_2	Response Time Out of LH_2	Remarks
1.	Minneapolis Honeywell capacitance probe.	160 msec.*	25 msec.	When the liquid moved parallel to the flatblade surfaces, the sensor indication was reliable and consistent. When the fluid moved perpendicular to the sensor plates the sensor time response was erratic.
2.	Transonic vibratory probe.	a) 150 msec. b) 100 msec.	400 msec. 300 msec.	a) With the protective shield b) Without protective shield
3.	Acoustica vibratory probe.	67 msec.	425 msec.	A chilldown period of at least twenty minutes was required prior to testing this probe.
4.	General Dynamics/ Electronics hot wire probe.	-	-	The probe was pulsed for 30 msec. every 100 msec. at a constant pulsing current of 600 M.A.

*milliseconds

GENERAL DYNAMICS/ELECTRONICS HOT WIRE
LIQUID-VAPOR SENSOR

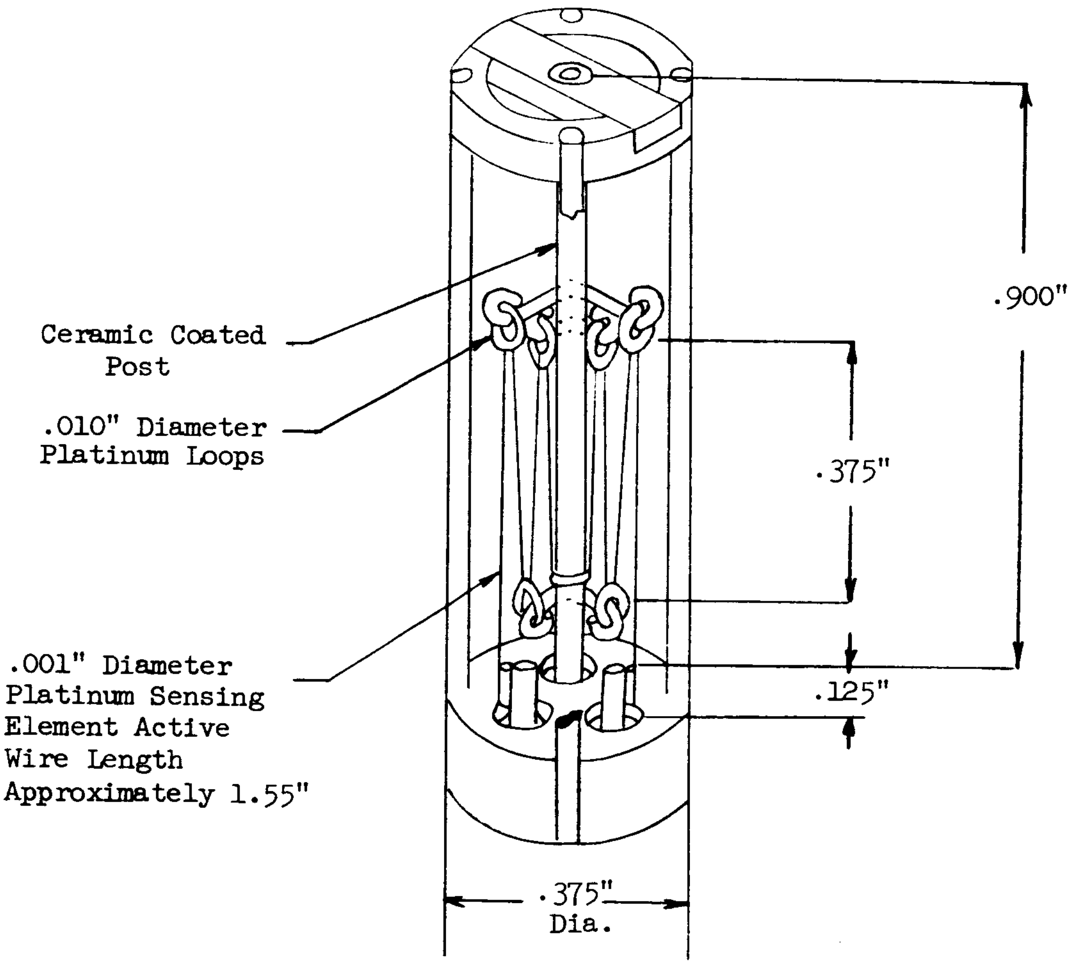


FIGURE 13

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